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A study of LNG processes to determine the effect of end flash systems on efficiency

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Abstract This paper describes the simulation, exergy analysis and comparison of two commonly applied liquefaction of technologies natural gas, namely: propane precooled mixed refrigerant process (C3MR) and dual mixed refrigerant process (DMR) alongside two modifications of each employing end flash systems. The C3MR and DMR process schemes were simulated using the commercial software to mathematically model chemical processes. These schemes were then analysed using energy and exergy calculations to determine their performances. The exergy efficiency for the C3MR processes without end flash system, with simple end flash system and extended end flash system were evaluated as 29%, 31%, and 33%, respectively, while the exergy efficiency for the DMR processes without end flash system, with simple end flash system, and extended end flash system were evaluated as 26%, 25.5%, and 30%, respectively. The results achieved show that the extended end flash system versions of the schemes are most efficient. Furthermore, the exergy analysis depicted that the major equipment that must be enhanced in order to improve the cycle exergy efficiencies are the compressors, heat exchangers, and coolers.

Keywords: C3MR; DMR; Efficiency; Exergy destruction; End flash; LNG

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Abbreviations

CMR	–	cold mixed refrigerant
C3MR	–	propane precooled mixed refrigerant process
DMR	–	dual mixed refrigerant process
LNG	–	liquefied natural gas
MCHE	–	main cryogenic heat exchanger
MR	–	mixed refrigerant process
NG	–	natural gas
SMR	–	single mixed refrigerant process
WMR	–	warm mixed refrigerant

1 Introduction

Global growth and development have given rise to massive consumption of goods and energy like natural gas. As more countries have encountered economic growth, population increase and widespread industrialization, as well as the demand for products has multiplied. It has been postulated that this demand will not drop but will continue to increase at faster rates. The U.S. Energy Information Administration's recently released [1] projects that world energy consumption will grow by 48% between 2012 and 2040. In the same document, consumption of natural gas worldwide is projected to increase from 120 trillion cubic feet (Tcf) in 2012 to 203 Tcf in 2040. This places natural gas as the energy source that accounts for the largest increase in world primary energy consumption. Natural gas is viewed by many environmentalists as a natural link between the fuels widely used today and the renewable fuels that would be dominant tomorrow. To produce at the rate that this growth demands, more efficient systems have to be developed and to preserve the environment those systems have to utilize less raw materials and fuel. In other words, a great objective of our future society is to develop sustainable methods of production of goods and ready for use energy. With the emergence of pipelines and liquefied natural gas (LNG), natural gas is a key international commodity that can meet its growing demand. Liquefied natural gas is traditional natural gas that has been cooled to liquefaction and hence, takes up about 1/600th the space that the same amount of gaseous natural gas would take up. In the gas sector, LNG is becoming increasingly important because it represents a means by which energy supplies can be diversified.

Thermodynamics, the science of energy conversion, exists as a key tool in achieving the objective of creating sustainable methods of production. In practice thermodynamics is often used to determine the performance of processes and plants [2,24-26]. However, to obtain the goal of developing sustainable production methods, determination of system performance is just the first step. Processes have to be analysed and optimised, and this necessitates the introduction of an additional quantity named 'exergy'. Exergy indicates energy quality and its importance becomes very clear during analysis and optimisation of energy systems as well as chemical processes. Simply put, the exergy of a system at a certain thermodynamic state is the maximum amount of work that can be obtained when the system moves from that particular state to a state of equilibrium with the surroundings [3,27]. Exergy is not subject to a conservation law (except for ideal, or reversible, processes), it is consumed or destroyed, due to irreversibilities in any real process. The exergy consumption during a process is proportional to the entropy created due to irreversibilities associated with the process. Exergy analysis is a method that uses the conservation of mass and conservation of energy principles together with the second law of thermodynamics for the analysis, design and improvement of energy use and other systems. The exergy associated with the energy quantity is a quantitative assessment of its usefulness or quality [4].

Liquefaction processes take raw feed gas, remove impurities and other components, cool the gas until it liquefies, and finally move the liquid into storage tanks from which they are transported more economically. Several studies have been carried out on liquefaction technologies to enhance opportunities so as to meet the increased demand for LNG. For example, Usama *et al.* [5] carried out a technology review of natural gas liquefaction processes. They reported the effects of tube side design pressure, end flash quantity, temperature approach in main condenser, LPG recovery, compressor efficiency, and liquefaction technology on LNG processes. They put forward that higher tube design pressure, greater quantity of end flash, closer temperature approach in main condenser, and increased compressor polytropic efficiency will enhance higher LNG production and lower specific power while LPG recovery will increase the power of LNG liquefaction and reduce LNG production.

Exergy analyses on different LNG processes have been undertaken also. Hollingworth *et al.* [6] depicted the benefits of exergy analysis and pointed out that the two major contributors to exergy destruction within an LNG train are the inlet and liquefaction facilities at 39% and 28%, respectively. Tsatsaronis and Morosuk [7] analysed a three cascade system for the liquefaction of natural gas using both conventional and advanced exergy analysis. The advanced exergy analysis enabled them to accurately determine what areas could be improved independently, hence, the information from the conventional exergy analysis was made more precise. Vatani and coworkers [8] applied an advanced exergy analysis to five LNG plants including the two base cases simulated in this project. Their results ranked mixed fluid cascade (51.82%) as the most efficient of the five processes, followed by propane precooled mixed refrigerant (C3MR) (50.98%), dual mixed refrigerant (DMR) (48.78%), single mixed refrigerant (SMR) process as developed by Air Products and Chemicals Inc. (APCI) (45.09%) and lastly, single mixed refrigerant as patented by Linde (40.2%) [8]. Results were also given for selected components of each process, and further investigation with advanced exergetic analysis was carried out. They concluded that structural optimization cannot be useful to decrease the overall process irreversibilities. Hamut *et al.* [9] evaluated existing and prospective processes for liquefaction of natural gas in Malaysia both thermodynamically and economically. The highest exergetic efficiency among the analysed systems was obtained in the C3MR process (33%). A newly designed LNG process, mixed refrigerant (MR-X) was also presented; it recorded an exergetic efficiency of 32%. Omar and colleagues [10] introduced a novel MR-X process for the liquefaction of LNG. Coefficient of the performance and the exergetic efficiency were found to be 0.58 and 32%, respectively. The relatively high values indicate that the novel process is an efficient one from a thermodynamic viewpoint.

Mafi *et al.* [11] carried out an exergy analysis for multicascade low temperature refrigeration systems with propylene and ethylene as refrigerants used in the olefin plant. The exergetic efficiency of the multistage cascade process was calculated to be 30.88%. With a mixed refrigerant as the refrigerant instead of ethylene, the exergetic efficiency increased to 34.04%, hence, it was proposed that the ethylene circuit be replaced. Konoglu [12] performed a comprehensive thermodynamic analysis of a multistage cascade refrigeration cycle and obtained an exergetic efficiency of 38.5%. Alabdulkareem *et al.* [13] also presented the simulation and optimization of the total energy consumption for a C3MR LNG plant. The pinch temperatures in heat exchangers were the decision variables for the study. Exergy efficiency of the overall system was given as 45.43% for the base cycle and 49.97% after the optimization. Remeljej and Hoadley [14] conducted the exergy analysis of small-scale LNG processes. They reported relative values from their comparative analysis between the small scale processes simulated; single mixed refrigerant cycle (SMR process), a nitrogen cycle (cLNG process) and two different open-loop cycles (new LNG scheme and gas consult limited (GCL)'s concept) [14].

This work undertook the exergy analysis of LNG configurations employing the propane precooled mixed refrigerant refrigeration system and modifications of this process with the inclusion of simple end flash and extended end flash system; and the dual mixed refrigerant system and its modifications with the inclusion of end flash systems. The C3MR system combines the best attributes of the cascade and mixed refrigerant (MR) processes. The addition of multiple refrigeration loops and mixed refrigerants aids in matching closely the cooling curve of the natural gas. The DMR process serves an alternative to the propane precooled mixed refrigerant for arctic climatic operation conditions which is characterized by low average annual temperature but relatively high temperature difference during the year. By accomplishing precooling and subcooling with two separate mixed refrigerants, the DMR process allows for more flexibility in selecting the precooling temperature and may allow a more optimum selection of compressors and drivers.

The difference between the configurations studied was in the presence or absence of end flash systems. In comparing these configurations, this work investigates whether the adoption of end flash systems which has been suggested for higher LNG yield also leads to higher exergy efficiency. These studies have not been carried out in terms of efficiency improvements with respect to the addition of end flash systems.

2 Process description

In the C3MR process, such as in the Nigeria LNG plant, propane refrigeration system is installed in series with a separate mixed refrigerant system. The process starts with the propane refrigeration loop which precools both the feed and the MR, and continues to a sub-cooling loop in which the MR liquefies the natural gas feed as seen in Figs. 1 and 2. In the DMR process, precooling and subcooling are accomplished by two separate mixed refrigerants as shown in Figs. 3 and 4. This process allows for more flexibility in selecting the precooling temperature and may allow a more optimum selection of compressors and drivers. Two end flash systems were considered, namely: the simple end flash system and the extended end flash system. In the extended flash system, LNG is produced from the main cryogenic heat

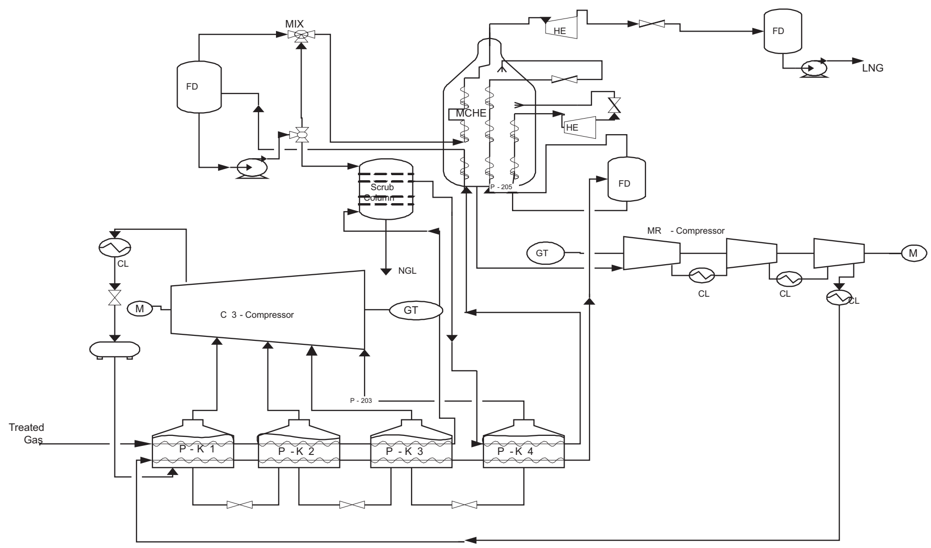

Figure 1: The C3MR process with no end flash system [15].

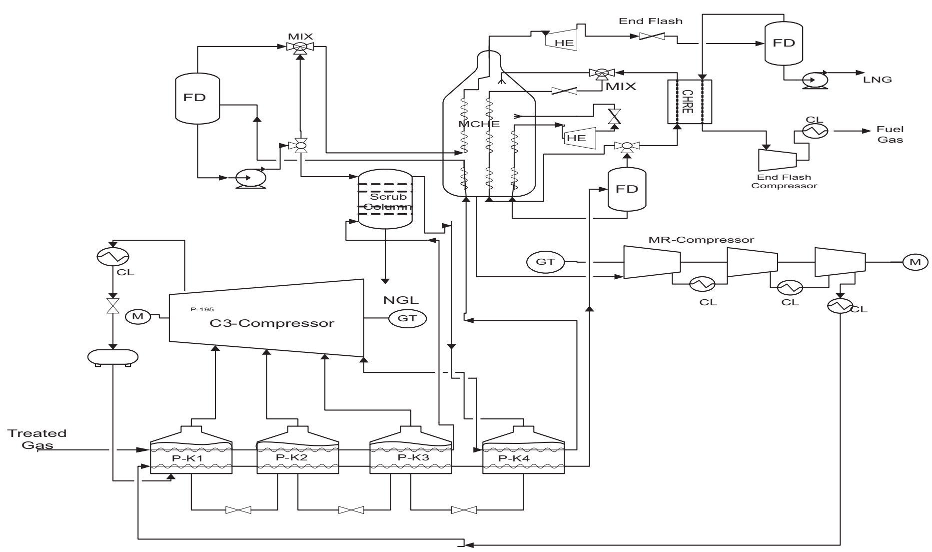

Figure 2: The C3MR process with flash gas production [15].

exchanger (MCHE) at lower temperature and is flashed after pressure reduction. The liquid phase is sent off as LNG to be stored while the vapour phase is sent through another heat exchanger for heat recovery before being

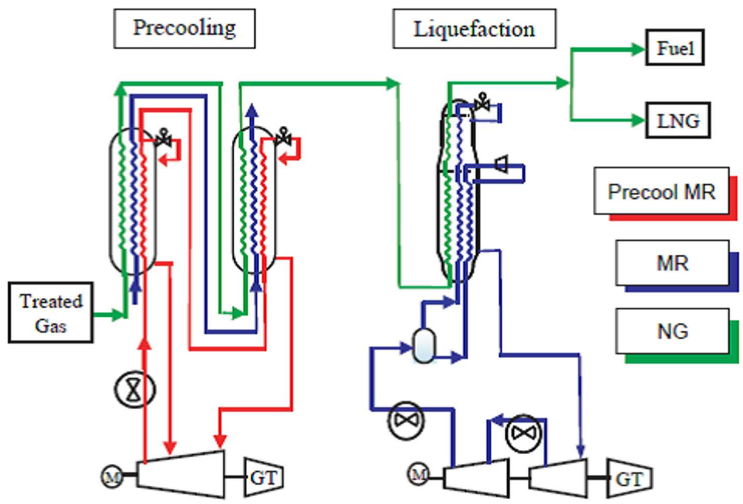

Figure 3: Schematic diagram of the shell DMR liquefaction process [16].

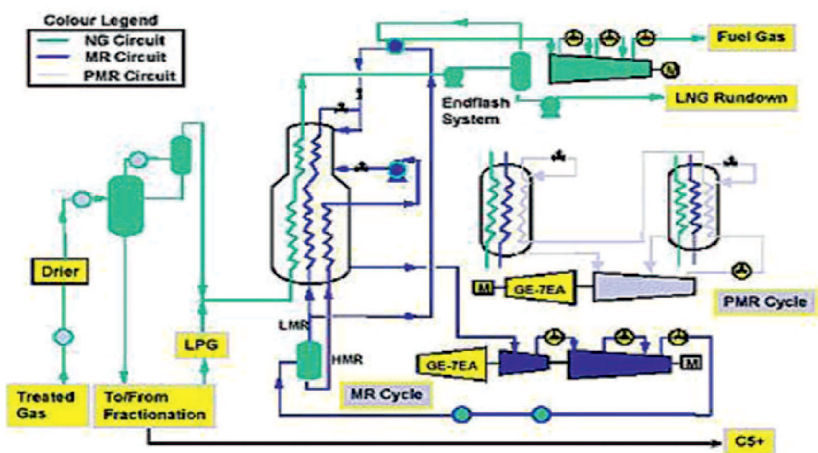

Figure 4: Schematic diagram of the shell DMR liquefaction process with flash gas production [17].

compressed to give gas. A portion of the compressed gas is sent off as fuel gas while the remainder is further compressed and recycled to mix with incoming LNG from the MCHE. In the simple end flash system, all the initially compressed gas is sent off as fuel gas without recycling and heat recovery.

3 Theory

Exergy is the maximum theoretical useful work (shaft work or electrical work) obtainable from a thermal system as it is brought into thermodynamic equilibrium with the environment while interacting with the environment only [9].

For a typical energy conversion system, the total exergy can be divided into four main parts physical, chemical, kinetic and potential exergy. However, for the process being considered in this study, it is assumed that kinetic and potential exergy are negligible and there are no chemical conversions. Hence physical exergies are sufficient for the exergetic analysis.

The energy rate of a stream is obtained from its specific value as

$$\dot{E} = \dot{m}_i \left(h_i - h_o\right) \ , \tag{1}$$

where $\dot{m}_i$ is the mass flow rate of stream i, $h_i$is the specific enthalpy of stream i at prevalent conditions, and h_o is the specific enthalpy at ambient conditions.

The energy balance on a unit is simply given as

$$\text{energy in} \ = \ \text{energy out in product} \ + \ \text{energy loss} \ . \tag{2}$$

The specific physical exergy of each stream i is evaluated from the following equation:

$$ex_i = \triangle h - T_o \triangle s = \left(h_i - h_o\right) - T_o \left(s_i - s_o\right), \tag{3}$$

where h is the enthalpy, s is the specific entropy, T_o is the ambient temperature, and the subscript o indicates conditions related to ambient temperature.

The total rate of the physical exergy in a stream is obtained from its specific value as:

$$\mathrm{Ex}_i = \dot{m}_i ex_i) \ , \tag{4}$$

$$\text{exergy destruction (irreversibility)} = \text{exergy source} - \text{exergy sink} \ , \tag{5}$$

$$\text{energetic efficiency} = \frac{\text{energy sink}}{\text{energy source}} \times 100\% \ , \tag{6}$$

$$\text{exergetic efficiency} = \frac{\text{exergy sink}}{\text{exergy source}} \times 100\% \ , \tag{7}$$

$$\mathrm{COP} = \frac{\mathrm{NG}_{feed} - \mathrm{NG}_{outlet\ from\ \mathrm{MCHE}}}{\text{Total Work}} \ , \tag{8}$$

$$\text{overall exergetic efficiency} = \frac{\text{Ex } [\text{LNG} - \text{NG}_{feed}]}{\text{Total Work}}, \tag{9}$$

where NG and LNG denote natural gas and liquefied natural gas output.

4 Methodology

4.1 Simulation

In this study, the C3MR and DMR processes and two modifications of each process were considered as references since they are prevalent in the LNG industry. The modifications involve the addition of a simple end flash unit and an extended end flash unit which are included in the industry to enhance production. The refrigerant conditions and operating parameters of the C3MR process and its modifications were found from data from the plant [15] while data for the DMR process and its modifications was obtained from literature [18]. This study did not cover the pretreatment process; hence it was assumed that the feed gas was a pretreated natural gas. The simulation of each proposed liquefaction cycle was based on natural gas supplied at 6200 kPa and inlet temperature of 45.5 °C with ambient temperature of 25 °C. The thermodynamic fluid package of Peng-Robinson was used for the simulation.

The base case simulation is based on the principle that generates little or no end flash gas, depending on nitrogen content of the feed gas. The process consists of a propane precooling unit and mixed refrigerant subcooling unit. The natural gas (NG) and mixed refrigerant (MR) both at high pressure levels are initially precooled by propane at four pressure levels in a propane circuit to the cut-point temperature of −35 °C. The natural gas is then further cooled by the mixed refrigerant cycle to −160 °C. The propane (C3) precooling unit is modelled with four multi-stream heat exchangers (LNG exchangers) operating at different pressure levels and three liquid/gas separator as shown in Fig. 5. The MR cycle which completes the liquefaction process prior to pressure reduction is modelled using three multi-stream LNG exchangers. Modelling the mixed refrigerant cooling unit with a single LNG exchanger did not allow for convergence on Aspen Hysys chemical process simulator as temperature crossovers occurred in the exchanger, hence, the unit was split into three stages. This method is confirmed in literature [19] with the use of two separate LNG exchangers.

This first modification involved the addition of an extended end flash unit to the C3MR process as modelled in the base case (Fig. 6). Based on acquired plant data, the cut point temperature for this process is −32.7 °C. In the model, LNG exits the MCHE at −152.4 °C and passes through a valve in which pressure is reduced to 1.15 bar before entering a flash vessel. The vapour and liquid phases are separated in the vessel. The vapour phase is sent into another LNG exchanger where cold is recovered and then compressed in a three-stage compression to about 2500 kPa. A fraction of the compressed flash gas is further compressed to 7000 kPa, sent back to be cooled against the cold flashed gas, reduced in pressure and recycled to mix with the incoming LNG from the MCHE into the flash vessel.

The second modification which was the addition of a simple end flash unit to the C3MR process was simulated similar to the extended end flash process. The cut-point temperature and LNG exit temperature were set at −32.7 °C and −145.4 °C, respectively. This unit is modelled by producing LNG from the MCHE at −145.4 °C, dropping pressure to 120 kPa and flashing in the end flash vessel. The vapour and liquid phases are separated. Vapour phase is then compressed to 2500 kPa and tagged as fuel gas.

The DMR liquefaction process is operated using two mixed refrigerants with different composition. The warm mixed refrigerant (WMR) contains higher boiling point components like propane and butane while the cold mixed refrigerant (CMR) contains mainly methane. The WMR undergoes compression in a two-stage compression unit to reach the working pressure of 2400 kPa while the CMR is compressed in a three-stage compression unit and enters the liquefaction unit at 5145 kPa. The compression units for the WMR and CMR are modelled with two and three interdependent compressors and coolers respectively.

In the base case (Fig. 7), the first cooling unit is modelled with a single LNG heat exchanger through which the natural gas feed and CMR are cooled from about 38 °C to −25 °C by the WMR. The WMR has a narrow working temperature and therefore only precools through a small temperature change. From the first heat exchanger, the precooled natural gas and CMR move to the second heat exchange cycle which is also modelled with a single LNG heat exchanger. These hot streams are cooled by the output of the CMR which undergoes a larger pressure drop compared to WMR, when passed through a choke valve. E xpansion reduces the temperature of CMR to −160 °C. The cold CMR subcools the precooled NG to −159 °C. The two modifications of the process are modelled as they were in the C3MR case. The second modification which is the inclusion of a simple end flash unit is shown in Fig. 8.

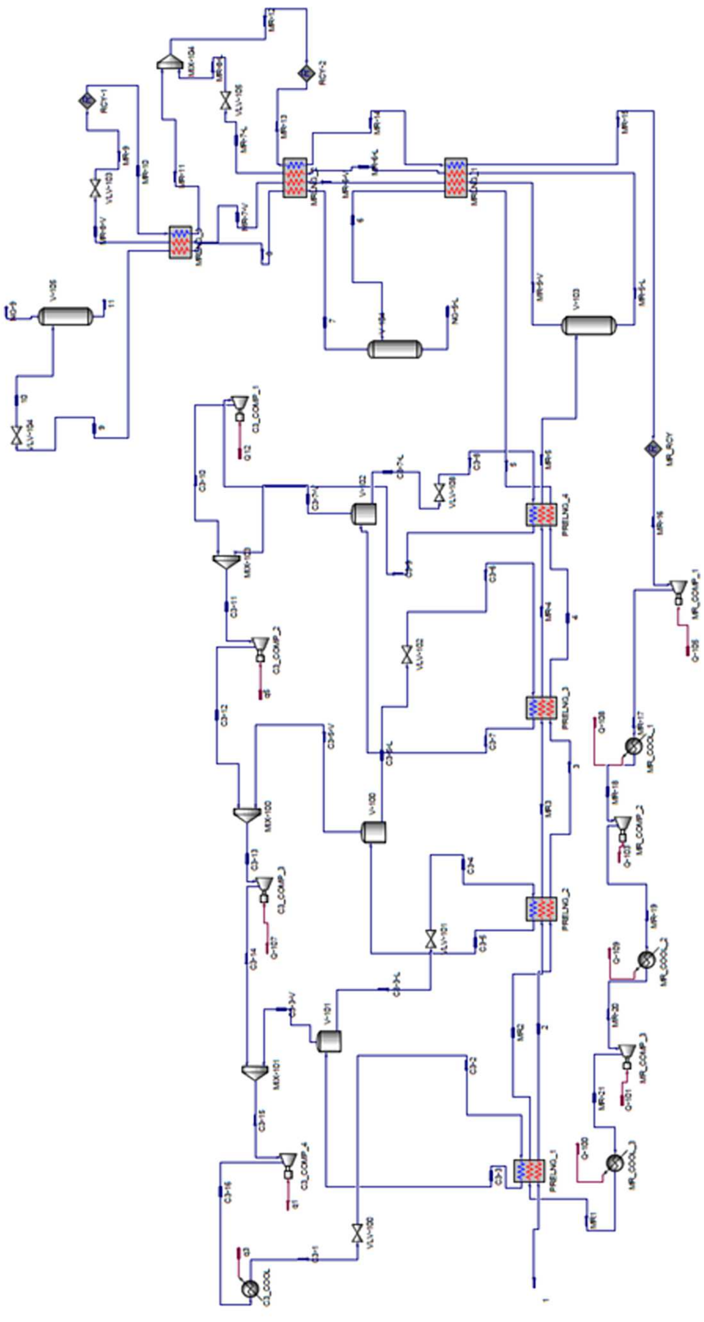

Figure 5: Schematic diagram of the shell DMR liquefaction process with flash gas production [17].

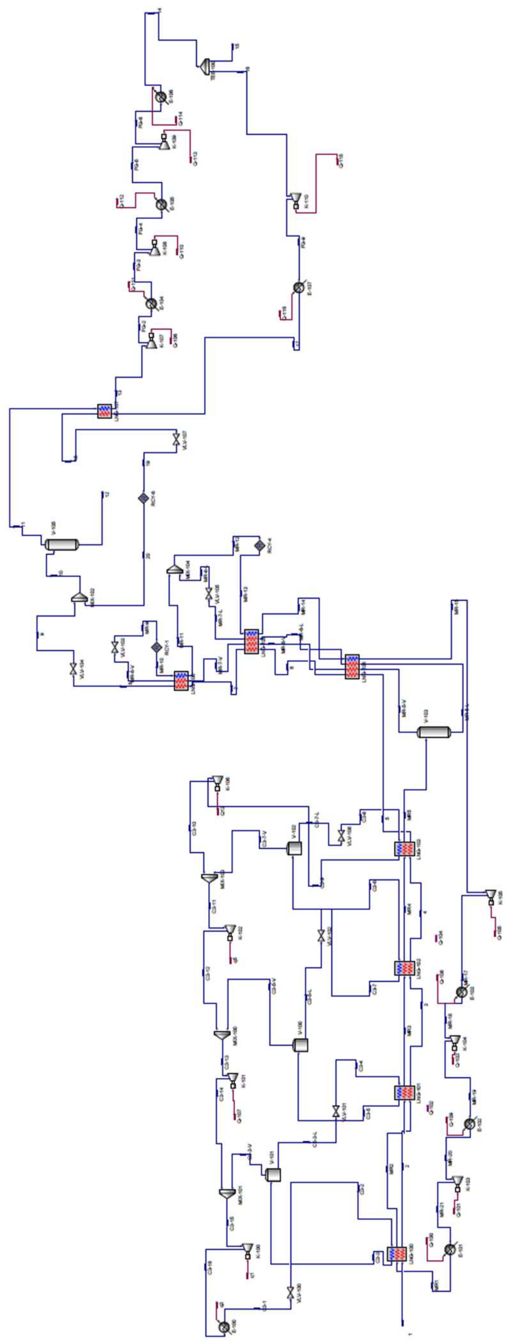

Figure 6: C3MR process with extended end flash unit flowersheet in simulation.

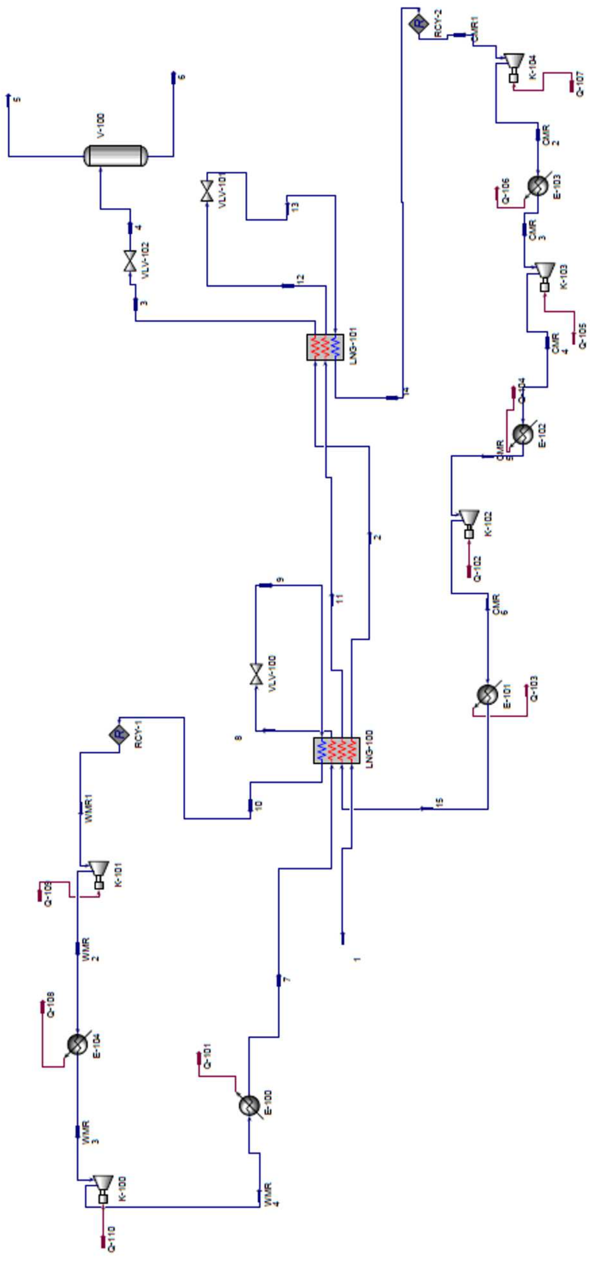

Figure 7: DMR process flowsheet in simulation.

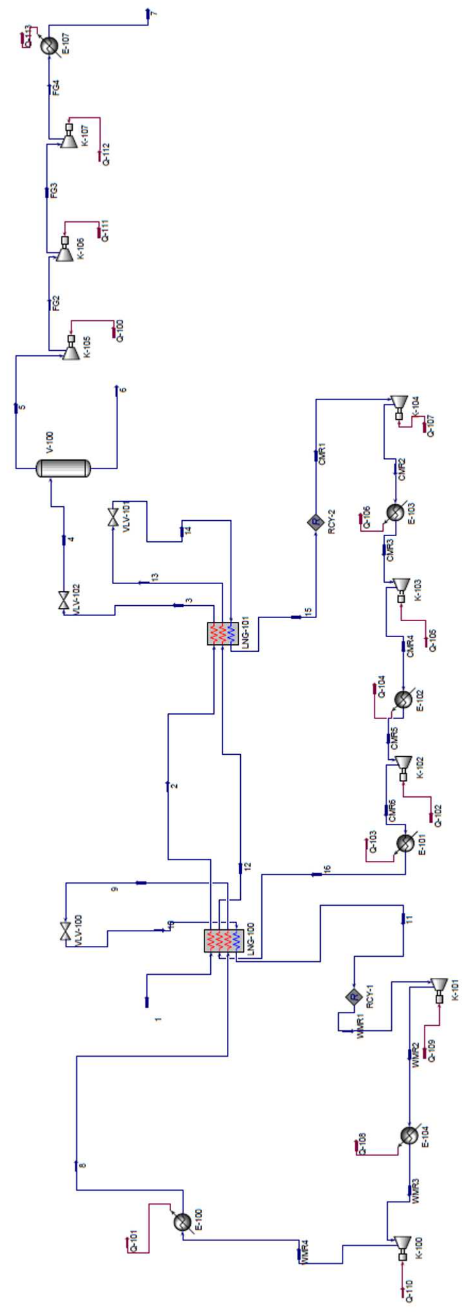

Figure 8: DMR process with simple and flash un it flowsheet in simulation.

4.2 Energy and exergy analyses

A popular spreadsheet package was used to perform the thermodynamic analysis of the systems after the required data, including the exergy which is a new property of updated versions of the software, was exported from commercial the chemical process simulator Aspen Hysys v8.6. The reference environment is based on Szargut *et al.* [21] and other papers [20,22]. Properties of major streams in each of the simulated cases are displayed in Tabs. 1–6.

Table 1: Parameters of major streams in the C3MR base case.

Stream name	Description	Temperature [°C]	Pressure [kPa]	Mass flow [kg/h]	Mass enthalpy [kJ/kg]	Mass entropy [kJ/kg°C]	Mass exergy [kJ/kg]
1	NG feed	45.5	6200	410223.94	-4189.63	8.59	557.03
2	Exit NG from first propane heat exchanger/ feed into the second propane heat exchanger	25.38	6165	410223.94	-4241.11	8.42	554.61
3	Exit NG from second propane heat exchanger/ Input into the third propane heat exchanger	5.25	6130	410223.94	-4293.92	8.24	555.75
4	Exit NG from third propane heat exchanger/ Input into last propane heat exchanger	-4.48	6095	410223.94	-4320.06	8.15	557.46
5	Exit NG from fourth (last) propane heat exchanger/ Input NG into the mixed refrigerant (MR) cycle	-35	6060	410223.94	-4412.22	7.79	573.49
6	Output NG from first MR heat exchanger	-45	6025	410223.94	-4448.82	7.63	583.20
7	Gas Output of separation of stream 6/ Input into the second MR heat exchanger	-45	6025	410223.94	-4448.82	7.63	583.20
8	Exit NG from second MR heat exchanger/ Input into the third MR heat exchanger	-127	5990	410223.94	-4919.76	5.17	846.67

continued Tab. 1

9	Exit NG from third MR heat exchanger	-160	5955	410223.94	-5026.12	4.35	985.58
10	Output of pressure reduction of stream 9	-163.32	120	410223.94	-5026.12	4.45	954.06
11	LNG	-163.32	120	389305.97	-5143.71	4.31	990.13

Table 2: Parameters of major streams in the C3MR case with simple end flash unit.

Stream name	Description	Temperature [°C]	Pressure [kPa]	Mass flow [kg/h]	Mass enthalpy [kJ/kg]	Mass entropy [kJ/kg^{o}C]	Mass exergy [kJ/kg]
1	NG feed	45.5	6200	569074.37	-4189.63	8.59	557.03
2	Exit NG from first propane heat exchanger/ feed into the second propane heat exchanger	25.38	6165	569074.37	-4241.11	8.42	554.61
3	Exit NG from second propane heat exchanger/ Input into the third propane heat exchanger	5.25	6130	569074.37	-4293.92	8.24	555.75
4	Exit NG from third propane heat exchanger/ Input into last propane heat exchanger	-4	6095	569074.37	-4318.73	8.16	557.31
5	Exit NG from fourth (last) propane heat exchanger/ Input NG into the MR cycle	-32.7	6060	569074.37	-4404.37	7.82	571.56
6	Output NG from first MR heat exchanger/Input into second MR heat exchanger	-45	6025	569074.37	-4448.82	7.63	583.20
7	Exit NG from second MR heat exchanger/ Input into the third MR heat exchanger	-127	5990	569074.37	-4919.76	5.17	846.67
8	Exit NG from third (and final) MR heat exchanger	-145.4	5955	569074.37	-4980.27	4.73	917.84
9	Output of pressure reduction of stream 8	-161.29	115	569074.37	-4980.27	4.87	876.31

continued Tab. 2

10	LNG obtained from flashing stream 9	-161.29	115	490601.00	-5173.46	4.34	975.78
11	Gas output obtained from flashing stream 9	-161.29	115	78473.36	-3772.50	8.16	210.18
12	Fuel gas obtained after three-stage compression	25	2490	78473.36	-3450.92	8.49	432.76

Table 3: Parameters of major streams in the C3MR case with extended end flash unit.

Stream name	Description	Temperature [°C]	Pressure [kPa]	Mass flow [kg/h]	Mass enthalpy [kJ/kg]	Mass entropy [kJ/kg^{o}C]	Mass exergy [kJ/kg]
1	NG feed	45.5	6200	617408.6	-4189.63	8.59	557.03
2	Exit NG from first propane heat exchanger/ feed into the second propane heat exchanger	25.38	6165	617408.6	-4241.11	8.42	554.61
3	Exit NG from second propane heat exchanger/ Input into the third propane heat exchanger	5.25	6130	617408.6	-4293.92	8.24	555.75
4	Exit NG from third propane heat exchanger/ Input into last propane heat exchanger	-4	6095	617408.6	-4318.73	8.16	557.31
5	Exit NG from fourth (last) propane heat exchanger/ Input NG into the MR cycle	-32.7	6060	617408.6	-4404.37	7.82	571.56
6	Output NG from first MR heat exchanger/Input into second MR heat exchanger	-45	6025	617408.6	-4448.82	7.63	583.20
7	Exit NG from second MR heat exchanger/ Input into the third MR heat exchanger	-127	5990	617408.6	-4919.76	5.17	846.67
8	Exit NG from third (and final) MR heat exchanger	-152.4	5955	617408.6	-5002.43	4.55	948.87
9	Output of pressure reduction of stream 8	-162.14	115	617408.6	-5002.43	4.67	913.42

continued Tab. 3

10	Output of mixing stream 9 (LNG with reduced pressure) and recycled NG stream	-163.36	115	713211.5	-4748.52	4.88	852.49
11	Vapour output from the separation of stream 10	-163.36	115	133817.2	-2987.2	7.36	196.06
12	LNG	-163.36	115	579394.3	-5155.32	4.30	990.56
13	Output of the heat exchange on stream 11 to recover cold	22.96	105	133817.2	-2678.15	9.04	4.50
14	Output of the three-stage compression of Stream 13	45.5	2490	133817.2	-2654.04	7.79	401.06
15	Portion of stream 14 extracted as fuel gas	45.5	2490	38017.59	-2654.04	7.79	401.06
16	Second portion of gtream 14 to be recycled into the cycle	45.5	2490	95799.65	-2654.04	7.79	401.06
17	Output of the compression and cooling of stream 16/ Stream sent back to the cycle to be cooled against the cold flashed gas (stream 11)	45.5	6990	95799.65	-2680.92	7.29	523.88
18	Output of heat exchange on stream 17	-99	6955	95799.65	-3112.62	5.35	669.86
19	Output of pressure reduction of stream 18	-166.20	115	95799.65	-3112.62	6.20	416.69
20	Stream recycled to mix with incoming LNG from MCHE (stream 9) into the flash vessel	-166.20	115	95802.9	-3112.22	6.20	416.54

Table 4: Parameters of major streams in the DMR base case.

Stream name	Description	Temperature [°C]	Pressure [kPa]	Mass flow [kg/h]	Mass enthalpy [kJ/kg]	Mass entropy [kJ/kg^{o}C]	Mass exergy [kJ/kg]
1	NG feed	38	5200	11920.78	-4112.64	8.07	494.42
2	Precooled NG from WMR heat exchanger/ Feed into the CMR cycle	-25	5150	11920.78	-4301.04	7.39	508.82
3	NG output from CMR heat exchanger	-159	4650	11920.78	-4932.86	3.95	902.52
4	Output of pressure reduction on stream 3	-159.32	120	11920.78	-4932.86	4.02	880.14

continued Tab. 4

5	Vapour output of separation of stream 4	-159.32	120	178.6287	-4275.00	8.64	222.86
6	LNG	-159.32	120	11742.15	-4942.87	3.95	889.38
7	Hot stream of WMR at high pressure	38	2978	35772.11	-2762.28	2.64	133.75
8	Output of heat exchange of stream 7 in WMR exchanger	-25	2928	35772.11	-2928.17	2.05	144.45
9	Cold stream of WMR obtained from pressure reduction of stream 8	-48.04	256.3	35772.11	-2928.15	2.09	134.10
10	WMR feed into the compression cycle/ warm output of WMR heat exchange cycle	25.31	246.3	35772.11	-2449.64	3.97	49.81
11	Precooled CMR from WMR heat exchange cycle	-25	5095	31664.67	-3066.82	4.95	374.17
12	Output of heat exchange of stream 11 in CMR heat exchanger	-160	4595	31664.67	-3483.65	2.66	638.98
13	Cold stream of CMR obtained from pressure reduction of stream 12	-164.36	341	31664.67	-3483.69	2.73	618.26
14	CMR feed into the compression cycle/ warm output of CMR heat exchange cycle	-29.15	331	31664.67	-2828.98	6.60	120.45
15	Hot stream of CMR at high pressure	38	5145	31664.67	-2784.57	5.98	348.76

Table 5: Parameters of major streams in the DMR case with simple end flash unit.

Stream name	Description	Temperature [°C]	Pressure [kPa]	Mass flow [kg/h]	Mass enthalpy [kJ/kg]	Mass entropy [kJ/kg^{o}C]	Mass exergy [kJ/kg]
1	NG feed	38	5200	13874.63	-4112.64	8.07	494.42
2	Precooled NG from WMR heat exchanger/ Feed into the CMR cycle	-22	5150	13874.63	-4289.34	7.43	506.55
3	NG output from CMR heat exchanger	-145.4	4650	13874.63	-4892.62	4.28	843.48
4	Output of pressure reduction on stream 3	-158.33	120	13874.63	-4892.62	4.38	815.54
5	Vapour output of separation of stream 4	-158.33	120	1262.52	-4750.82	9.08	231.58

continued Tab. 5

6	Liquefied natural gas	-158.33	120	12612.11	-4906.81	3.903896	871.07
7	Fuel gas obtained from three-stage compression of stream 5	30	2390	1262.52	-4385.71	9.51	468.03
8	Hot stream of WMR at high pressure	43	2900	43072.98	-2746.37	2.70	134.38
9	Output of heat exchange of stream 8 in WMR exchanger	-22	2850	43072.98	-2921.25	2.08	142.94
10	Cold stream of WMR obtained from pressure reduction of stream 9	-36.97	400	43072.98	-2921.25	2.10	135.90
11	WMR feed into the compression cycle/ Warm output of WMR heat exchange cycle	35.29	390	43072.98	-2435.61	3.94	75.25
12	Precooled CMR from WMR heat exchange cycle	-22	5095	39253.72	-3051.35	5.01	371.16
13	Output of heat exchange of stream 12 in CMR heat exchanger	-145.4	4595	39253.72	-3451.04	2.93	590.79
14	Cold stream of CMR obtained from pressure reduction of stream 13	-151.15	550	39253.72	-3451.04	3.00	571.30
15	CMR feed into the compression cycle/ Warm output of CMR heat exchange cycle	-32.19	540	39253.72	-2838.12	6.41	167.13
16	Hot stream of CMR at high pressure	43	5145	39253.72	-2772.8	6.02	349.34

Table 6: Parameters of major streams in the DMR case with extended end flash unit.

Stream name	Description	Temperature [°C]	Pressure [kPa]	Mass flow [kg/h]	Mass enthalpy [kJ/kg]	Mass entropy [kJ/kg^{o}C]	Mass exergy [kJ/kg]
1	NG feed	38	5200	11920.78	-4112.64	8.07	494.42
2	Precooled NG from WMR heat exchanger/ Feed into the CMR cycle	-22	5150	11920.78	-4289.34	7.43	506.55
3	NG output from CMR heat exchanger	-152.4	4650	11920.78	-4913.46	4.11	872.66
4	Output of pressure reduction on stream 3	-160.85	100	11920.78	-4913.46	4.20	847.29

continued Tab. 6

5	Output of mixing stream 4 (LNG with reduced pressure) and recycled NG stream	-161.10	100	12818.9	-4896.89	4.43	822.68
6	LNG	-161.10	100	11422.77	-4942.13	3.88	893.79
7	Vapour output from the separation of stream 5	-161.10	100	1396.14	-4526.76	8.93	207.70
8	Output of the heat exchange on tream 7 to recover cold	0.59	90	1396.14	-4204.46	10.76	-15.2123
9	Output of the three-stage compression of stream 8	43	2390	1396.14	-4136.24	9.39	459.70
10	Portion of stream 9 extracted as fuel gas	43	2390	505.19	-4136.24	9.39	459.70
11	Second portion of stream 9 to be recycled into the cycle	43	2390	890.95	-4136.24	9.39	459.70
12	Output of the compression and cooling of stream 11/ Stream sent back to the cycle to be cooled against the cold flashed gas (stream 7)	43	6990	890.95	-4177.08	8.77	605.28
13	Output of heat exchange on stream 12	-85	6940	890.95	-4682.14	6.59	
14	Output of pressure reduction of stream 13	-162.93	100	890.95	-4682.14	7.52	471.70
15	Stream recycled to mix with incoming LNG from MCHE (stream 4) into the flash vessel	-162.95	100	898.12	-4676.9	7.52	471.98

The irreversibilities and exergetic efficiencies were computed for each component and the overall system. The contributions of the individual unit operations to the overall exergy destruction were also computed.

The equations in the theory section were used in calculating the energetic and exergetic efficiencies of the processes. The implications of the equations were different for the individual unit operations; these implications are displayed in Tab. 7.

Table 7: Identification of exergy source and sink and irreversibility for the units.

Equipment	Exergy source	Exergy sink	Irreversibility
Heat exchanger	Ex [hot stream outlet – hot stream inlet]	Ex [cold stream inlet – cold stream outlet]	Ex [hot stream inlet – hot stream outlet] – Ex [cold stream outlet – cold stream inlet]
Compressor	W_s [supplied work]	Ex [compressor outlet – compressor inlet]	W_s [supplied work] – Ex [compressor outlet – compressor inlet]
Cooler	Ex [cooler inlet – cooler outlet]	Ex [exergy of heat released]	Ex [cooler inlet – cooler outlet] – Ex [exergy of heat released]
Valve	Ex [valve inlet]	Ex [valve outlet]	Ex [valve inlet] – Ex [valve outlet]
Separator	Ex [separator inlet]	Ex [vapour outlet + liquid outlet]	Ex [separator inlet] – Ex [vapour outlet + liquid outlet]
Mixer	Ex [sum of mixer inlets]	Ex [sum of mixer outlets]	Ex [sum of mixer inlets] – Ex [sum of mixer outlets]

5 Results and discussion

5.1 Results of thermodynamic analysis of C3MR process schemes

The results of the efficiency analyses for the C3MR processes are tabulated in Tab. 8. The version adopting the no end flash gas recorded the lowest value of energetic efficiency (64%), followed by the extended end flash system (69%) while the simple end flash system had the highest energetic efficiency (79%). The simple end flash is a hypothetical scenario; the highest feed rate based on the conditions available was chosen, hence the high energetic efficiency. With increase in feed rate into the C3MR extended end flash system, the energetic efficiency was also seen to increase.

This implies that it can handle more than the current processing rate. The C3MR without end flash has the lowest energetic efficiency due to the fact that the energy imbalance is most significant in this scheme. Given the same amount of power to all three schemes as seen in the NLNG plant, the C3MR process without end flash uses the least, and thereby wasted the most energy. Although some amount of energy is also wasted in the other

Table 8: Results of energy and exergy analyses for the three C3MR process schemes.

	No end flash (base case)	Simple end flash	Extended end flash
Work supplied (overall exergy of fuel) [MW]	149.23	154.77	188.60
Work utilized (overall exergy of product) [MW]	45.60	47.75	62.76
Overall exergy destruction [MW]	105.63	107.02	125.84
Exergy destruction/LNG produced [kWh/ton LNG]	271.32	217.37	227.28
Process energy efficiency [%]	63.87	79.38	68.71
Process exergy efficiency [%]	29.22	30.85	33.28
Rank (exergy efficiency)	3rd	2nd	1st

two schemes, the effect is less pronounced since the schemes can process more NG and thus produce more LNG. However, the range of energy efficiency (60–80%) is quite high compared to the exergy efficiency. It can be deduced that although, the energy efficiencies give some information, they are not the most accurate measures of performance. The C3MR with extended end flash system is the most exergetically efficient (33%), followed by the simple flash system (31%), while the C3MR process with no end flash is the least efficient (29%). Hence, the adoption of the C3MR process with extended end flash system is favoured.

The exergy efficiencies as calculated in this study compare favourably with the values in literature which range from 30–50% [9,13,23]. The differences in exact values are definitely caused by process conditions and simulation assumptions. The exergy efficiencies measure the thermodynamic irreversibilities in the three process schemes. The conclusions in this study are not different from those given in literature. The fact is there is still a lot of progress to be made, despite advanced modifications into various liquefaction cycles. The end flash systems are modifications of the basic C3MR process; other modifications include the new AP-X and MR-X methods [9]. The C3MR process with extended end flash is the most efficient, however, it still has significant exergy destruction and it is important to study how this can be saved. The exergy destruction for all processes were further broken down so as to quantify existing potentials for enhancing the cycle's performance.

The distribution of exergy destruction follows a similar pattern for the three schemes. The bulk of exergy destruction occurred in the heat exchangers, compressors and dissipative elements (coolers and mixers) as shown in Fig. 9, which is consistent with literature [10]. Therefore, technology to enhance the processes must be concentrated on these three groups of equipment. The exergy destruction for the C3MR processes without end flash system, with simple end flash system and extended end flash system were evaluated as 106 MW, 107 MW, and 126 MW, respectively.

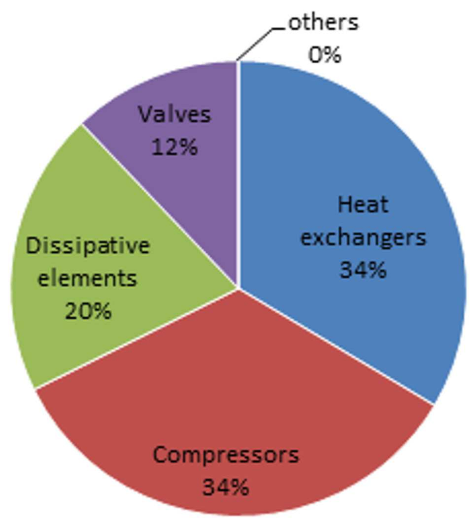

Figure 9: Aggregate exergy destruction of equipment in C3MR process with no end flash.

5.2 Results of thermodynamic analysis of DMR process schemes

The results of the efficiency analyses for the DMR processes are tabulated in Tab. 9. The DMR version without an end flash system recorded the lowest energetic efficiency (56%) while the two end flash systems recorded similar values of 65%. As in the C3MR case, the low value of energy efficiency recorded for the DMR process with no end flash system is due to the energy imbalance and the underutilization of available energy. Energy is also wasted in the other two schemes; however, this is balanced by the increased production rates. The energy efficiencies obtained for the process schemes are higher than the exergy efficiencies, therefore it is obvious that there are irreversibilities in the processes that the energy efficiencies do not account for. The DMR process with extended end flash system is the most exergetically efficient (30%), while the DMR process with simple end flash system has the lowest value (25.5%) and the process with no end flash system is slightly better than the process with simple end flash (26%). Therefore, the adoption of the DMR process with extended end flash system is clearly favoured. Unlike the C3MR process, a lot of work has not been done on the exergy analysis of the DMR process. The exergy efficiencies which are measures of thermodynamic irreversibilities show that there is still a lot to be done in making the DMR processes efficient. To study the main sources of the irreversibilities, the exergy destructions for all the processes were further broken down.

Table 9: Results of energy and exergy analyses for the three DMR process schemes.

	No end flash (base case)	Simple end flash	Extended end flash
Work supplied (overall exergy of fuel) [kW]	4853.60	4689.00	4768.59
Work utilized (overall exergy of product) [kW]	1263.71	1196.53	1437.30
Overall exergy destruction [kW]	3589.89	3492.47	3331.29
Exergy destruction/LNG produced [kWh/ton LNG]	305.72	273.29	245.72
Process energy efficiency [%]	55.96	64.82	65.28
Process exergy efficiency[(%]	26.03	25.52	30.14
Rank (exergy efficiency)	2nd	3rd	1st

The distribution of exergy destruction follows a similar pattern for all three schemes; the pattern is consistent with what was observed for the C3MR process schemes. The equipment with the highest exergy destruction are the heat exchangers, compressors and dissipative elements (coolers). Improvement efforts must be focused on these three groups of equipment. As suggested earlier, to improve the coolers' exergy destruction which is dependent on the exergy content of the cooling duty, the compressors' efficiency should be increased. The exergy destruction for the DMR processes without end flash system, with simple end flash system and extended end flash system were evaluated as 3590 MW, 3492 MW, and 3331 MW, respectively.

5.3 Comparison of DMR schemes and C3MR schemes

The first law and exergetic efficiencies for both process schemes are shown in Tab. 10. The base case results are consistent with literature [8]. In the base cases and modifications studied, the first law efficiencies and exergy efficiencies of C3MR were higher than those of DMR. However, the variation patterns of first law energy efficiencies and exergy efficiencies with process schemes of C3MR and DMR refrigeration systems were opposite. For C3MR systems, energy efficiency increased and decreased while exergy efficiency increased linearly in moving from the base case to the base case with extended end flash. For DMR systems, energy efficiency increased linearly while exergy efficiency decreased and increased in moving from the base case to the base case with extended end flash. The exergetic efficiencies were all lower than those of the first law efficiency which is a result of the inclusion of the second law of thermodynamics in the exergetic analysis to give the true quality of the energy. In terms of both first law efficiency and exergetic efficiency, extension of the flash end gas production unit seems to have a better effect on the DMR process. However, in the industry, DMR processes and C3MR processes serve different functions. DMR is usually used offshore for large amount of natural gas processing while C3MR dominates onshore applications.

Table 10: Energy and exergy efficiencies of all modelled process schemes.

	Energy efficiency [%]	Exergy efficiency [%]
C3MR base case	63 87	29.22
C3MR with end flash unit	79.38	30.85
C3MR with extended end flash unit	68.71	33.28
DMR base case	55.96	26.04
DMR with end flash unit	64.82	25.52
DMR with extended end flash unit	65.28	30.14

6 Conclusions

This project has shown that the performance of a LNG plant is best assessed via plant exergy efficiency and not energy efficiency. It was revealed that for both propane precooled mixed refrigerant (C3MR) and dual mixed refrigerant (DMR) process schemes, adopting the extended end flash unit gives the highest efficiency. The need for the study was justified as sources of irreversibilities were discovered.

The exergy destruction and exergy efficiency for the propane precooled mixed refrigerant processes without end flash system, with simple end flash system and extended end flash system were evaluated as 106 MW, 107 MW, 126 MW and 29%, 31%, and 33%, respectively.

The exergy destruction and exergy efficiency for the dual mixed refrigerant processes without end flash system, with simple end flash system and extended end flash system were evaluated as 3590 MW, 3492 MW, 3331 MW and 26%, 25.5% and 30%, respectively. The exergetic efficiencies obtained for both process schemes are consistent with literature [8]. The increasing order of efficiency achieved with the end flash systems is also as expected based on [5].

The major equipment that must be enhanced so as to improve the cycle exergy efficiencies are the compressors, heat exchangers, and coolers. Upgrading process schemes without end flash systems, increasing compressors' efficiency and adjusting refrigerant compositions are options to be considered for the cycle performance improvement.

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