The International Journal of Engineering and Science (IJES)
|| Volume || 12 || Issue || 2 || February || Pages || PP 32-43 || 2023 ||
ISSN (e): 2319-1813 ISSN (p): 20-24-1805

Investigation of the comparative performance of a modified propane precooled mixed refrigerant (C3-MR) natural gas liquefaction plant located in Algeria

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---ABSTRACT---

Large scale production of liquefied natural gas (LNG) typically employs energy-intensive cascade refrigeration cycles such as the Propane Precooled Mixed Refrigerant (C3-MR)cycle. Previous work has focused on improving the energy efficiency of this cascade-type cycle since it can bring significant economic benefits. However, potential benefits associated with changes in the configuration of the mixed refrigerant loop of the C3-MR cycle are usually neglected. This work investigatestwoC3-MR cycle options, based on structural modifications of the MR loop, to see how competitivea modified process will be with abase case process. The chosen configurations are the base case C3-MR cycle with two MR compressors and the modified case cycle with a single compressor. The performance of these two cycles is evaluated using a case study of an LNG plant in Algeria. The analysis uses a proprietary steady state simulator for modelling. It can be found that the specific power of 831.6 kWh/ton LNG and the coefficient of performance (COP) of 1.33 are achieved in base case and the specific power of 981.3 kWh/ton LNG and the COP of 1.28 are achieved in modified case by comparing the two cases. The results of the modified design implemented on the baseload LNG plant give specific power and COP values that are18% smaller and 4% larger than the original design. The results obtained demonstrate that the structural changes does not enable the modified cycle to achieve better energy savings, rather there is a loss compared to the base case C3-MR cycle.

KEYWORDS;-*LNG, Baseload LNG Plant, Natural Gas Liquefaction, Technical evaluation.*

Date of Submission: 09-02-2023 Date of Acceptance: 20-02-2023

I. INTRODUCTION

Natural gas consumption is rapidly increasing and, as a transition fuel, will become the second largest source of fossil fuel in the world by 2030[1]. This growth in demand is attributed to the significantly lower carbon dioxide emissions associated with itsuse[1]. Consequently, liquefied natural gas (LNG) production is also increasing steadily as a key technology for natural gas transportation. LNG is cheaper than other transportation alternatives such as pipeline natural gas above some critical distances between the gas supplier and gas buyer [2]. The current largest, global LNG importer is China.Natural gas inflows to China (as LNG) in 2018, for example, reached 72.8 billion cubic meters[3]. Several LNG projects are planned and will, hopefully, be executed to support the growing demand for LNG [4].

LNG is produced through the process of natural gas refrigeration, where natural gas is cooled to a temperature of approximately -161^{0}C to form LNG. Proprietary technologies exist for large scale LNG production, some of which are: the Propane Precooled Mixed Refrigerant (C3-MR) cycle [5], the Dual Mixed Refrigerant (DMR) cycle [6], and the Phillips Cascade cycle [7]. Single and multi-components refrigerants can be used for the refrigeration process and the use of compressors for refrigerant compression are routine but the compression process is a key contributor to the operating costs of the entire baseload LNG facility [8]. Therefore, it is important to consider minimizing the shaft power demand (usually a performance indicator in the refrigeration process) in order to achieve significant savings in operating costs. High efficiencies of the process are achieved at lower shaft power.

Researchers has focused on improving the energy efficiency of the C3-MR process. Mortazavi et al. [9] has studied the propane precooled mixed refrigerant (C3MR) cycle's potential reductions in shaft power demand using absorption chillers instead of two cooling stages in the precooling cycle. They also evaluated opportunities for shaft power savings by replacing throttle valves with liquid turbines in the precooling cycle [10]. Alabdulkarem et al. [11] used a genetic algorithm to optimized same conventional C3-MR cycle, obtaining a 9% reduction in shaft power demand.Wang et al. [12] developed a methodology for a C3-MR cycle, that uses temperature-enthalpy diagrams of the refrigerants and the composite curves to indicate adequate upper and lower bounds for the operating variables prior to optimization and Wang et al. [13] subsequently optimized a C3-MR cycle using linear and quadratic regressions to model the thermodynamic properties of mixed refrigerants. Hatcher et al. [14] used different objective functions, including minimum power demand, toevaluate the performance of a C3-MR process. Lim et al. [15] improved the energy-efficiency of a C3-MR cycle by using the end flash gas of the LNG to provide cooling at different locations in the process. He and Lin [16] optimized a C3-MR cycle for minimum shaft power demand to produce LNG together with high-purity ethane. Fahmy et al. [17] investigated the number of precooling stages and the propane subcooling temperature to improve energy efficiency. Wang et al. [18] optimized two C3-MR cycles, with three and four cooling stages in the precooling cycle, considering fixed sizes for the multi-stream heat exchangers (MSHE).

None of the reviewed studies investigated the effect of changing the mixed refrigerant loop configuration on the technical performance of the liquefaction process. This is important as there has been questions as to how a modified or replaced equipment in the mixed refrigerant loop could affect the performance of the C3-MR process. Theseresult and issues motivate the currentinvestigation of the comparative performance of a modified, baseload propane precooled mixed refrigerant liquefaction plant where the dual compressor in the mixed refrigerant loop configuration is altered by using a single compressor. This work uses the case study of an operational, baseload LNG plant in Algeria and a proprietary steady state simulator to assess the technical performance of the dual mixed-refrigerant compressor of the C3-MR process against the modified process deploying a single mixed refrigerant compressor system. This paper is structured as follows: Section II introduces the methods and configurations developed in this work. Section III analyses results and demonstrates the performance of the two configurations. Section IV presents the conclusions obtained from this work.

II. MATERIALS AND METHODS

Natural gas liquefaction process and LNG properties and behaviour

Following the removal of most contaminants and heavy hydrocarbons from the feed gas in a typical baseload LNG facility, the natural gas advances within the facility to undergo the liquefaction process [19, 20]. The natural gas being converted to its liquefied form is almost entirely methane at this point. Thenatural gas has to be liquefied through the application of refrigeration technology. LNG, once produced, is a non-corrosive liquid that is clear and colourless like water, but weighs about half as much as the same volume of water. One volume of LNG equals approximately 600 volumes of natural gas at standard temperature (15.6 C / 60 F) and atmospheric pressure. This essentially means that the LNG occupies a volume 600 times smaller than the same amount of natural gas. It is this ratio of liquid to gas that makes LNG economically attractive for transporting bulk volumes by ship or truck.

Propane precooled mixed refrigerant (C3-MR) natural gas liquefaction process.

To facilitate the understanding of C3-MR process, we first present in Fig. 1, a simplified, typical schematic of the propane precooled mixed refrigerant natural gas liquefaction process [19]. This liquefaction technology dominates the industry and is licensed by Air Products and Chemicals Inc. (APCI) [19]. This process contains two refrigeration cycles. The first - the precooling cycle uses a pure component propane. The second - the liquefaction and subcooling cycle uses a mixed refrigerant composed of nitrogen, methane, ethane, and propane. For liquefaction train capacities up to five million tonnes per annum, the C3-MR process has been the dominant technology. It utilizes a single Air Products coil wound heat exchanger to liquefy the natural gas. Plants could use two GE Frame 7 gas turbine drivers [19]. The C3-MR process has been used in several LNG plants including in Egypt, Nigeria, Peru, Yemen, Papua New Guinea and Algeria [19]. The C3-MR process operates efficiently in arid and tropical climates, with rich and lean natural gas feed, with and without NGL and LPG extraction, over a broad range of ambient temperatures [19].

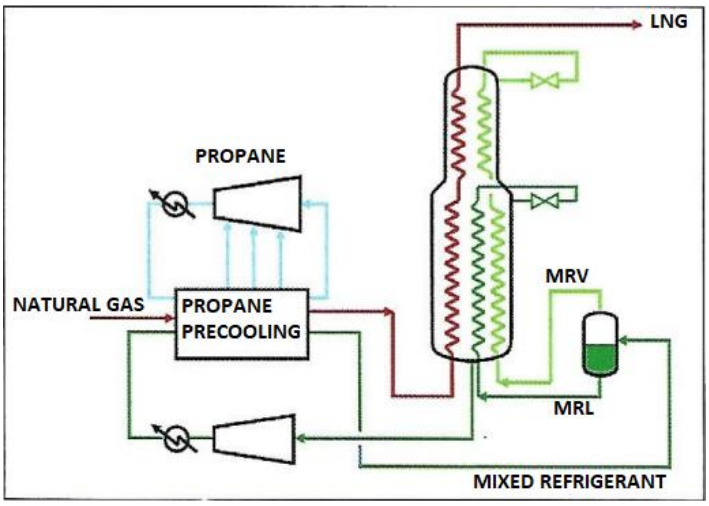

Fig. 1: A simplified flowsheet of the C3-MR process [19]

Fig. 2 is used for further simplification and better description of the C3-MR process, and with legends that indicate fluid path.Observe the first block which is the pre-cooling block, which uses propane as its refrigerant. The second block uses mixed-refrigerant to liquefy and successively sub-cool, in the central heat exchanger known as the Main Cryogenic Heat Exchanger (MCHE).Typically, and before entering the liquefaction unit, the feed natural gas (NG) undergoes the pre-treatment process (not shown in Fig. 2). In the pre-treatment process, acid gas is removed first from the NG. It then proceeds to dehydration (water removal) and mercury removal processes. After that, natural gas liquids (NGL) are withdrawn from the NG. The NGL normally is sent to distillations sequences where various by-products such as Ethane and LPG among others, are separated. The pre-treated NG is fed into the pre-cooling block within the C#-MR process and the mixed-refrigerant coming from the MCHE is also fed into this pre-cooling block. Both feeds' temperatures produced from this block are about -40°C.

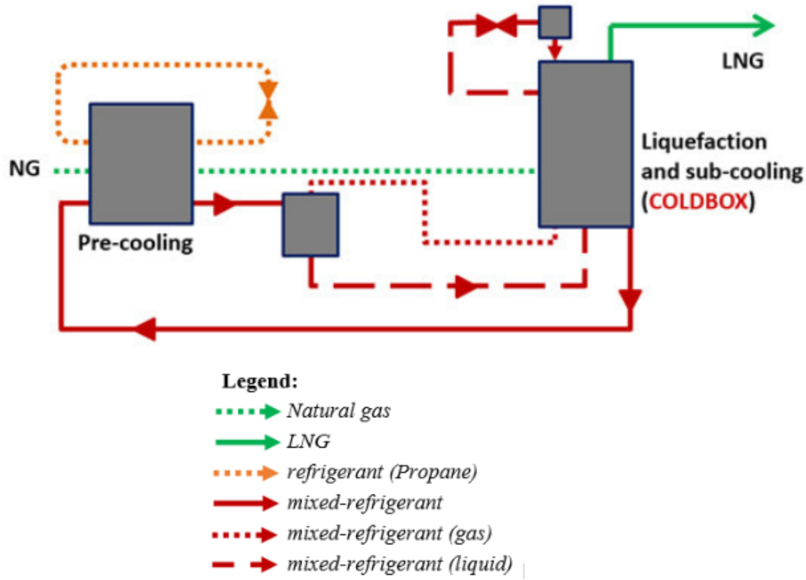

Fig. 2: A general schematic/block diagram of the C3-MR process with legends.

Throughout the cycles (including liquefaction), heat is removed using seawater through inter- and after-coolers, to the environment. The pre-cooled natural gas (NG) is fed into the MCHE to be liquefied and sub-cooled. The mixed refrigerant (MR)leaving the pre-cooling block is split into light and heavy fluids in a phase separator before both streams flow into the MCHE. Upon liquefying and subcooling the natural gas, the vaporized- and liquid-phase mixed-refrigerants recombine at the exit (bottom catchment) of the MCHE and then looped back afterwards into the pre-cooling block driven by compressors in two stages (i.e. dual compressor system). The sub-cooled LNG exits the MCHE at a temperature ofapprox. -162 Celsius and at slightly above ambient pressure. Thereafter, the final LNG product is ready for storage and for subsequent transportation to buyers via LNG ships or trucks. Other targets may be implemented such as recycling flashed LNG into the system for powering local electricity sources or processed further for by-products.

Case study for evaluating the comparative performance of a modified liquefaction process

Algerian Case Study

The case study in this project is Sonatrach's GL2Z LNG Plant in Arzew, Algeria. This is a liquefaction plant containing three pressure stages (of evaporators) in the propane precooling block (not shown), and two compressors in the mixed refrigerant block (also not shown in Fig. 2). Our goal is to simulate this same plant set-up using reliable data sourced from literature. We used the actual flowsheet of this plant but due to confidentiality of the data, we will not be presenting the flowsheet here. Though the unit looks similar to what is shown in figures 1 and 2, except for some keyequipment and pressure vessels in the original plant including high, medium, and low-pressure evaporators, natural gas liquid (NGL) removal unit, dehydration unit, knock out drums and mixed refrigerant compressorsthat are not shown.

Simulation and Energy Analysis Software

A proprietary steady-state simulator is chosen to model and simulate the real plant. For initialization, the ***Peng-Robinson*** property method, is selected for this C3-MR process simulation. Generally, Peng-Robinson is recommended for gas applications, as it can calculate the enthalpy and entropy values of the process streams, and it is appropriate for a mixture of non-polar or mildly-polar fluids. It is consistent even in the critical region, and reasonable results can be found at all pressures and temperature. For the modelling and simulation runs, the following assumptions and specifications are used:

1. The ambient temperature and pressure are set as 25^{o}C (298. 15 K) and 1.01325 bar, respectively.
2. Pressure drops throughout all heat exchangers are assumed to be 0 for simplicity.
3. It is also assumed that no pressure loss occurs within mixers, and that all phase separations are specified to have no heating duty.
4. The isentropic efficiencies are assumed to be 78% (propane compressors) and 75% (mixed-refrigerant compressors).
5. The discharge pressures for propane compressors are specified as 3.8 – 8 – 20 bar, and for mixed-refrigerant compressors are as 5 – 30 bar.
6. The initial values necessary to simulate NG feed, propane and mixed-refrigerant mass flows are regulated according to a common LNG train capacity that used C3-MR process, which is at 1.4 mtpa. As such, the propane mass flow is specified as 193.3 kg/s, the mixed-refrigerant mass flow as 201.4 kg/s, and the NG feed mass flow is specified as 57.99 kg/s at 15 bar and 301.1 K (28^{0}C)
7. The NG and MR compositions for this process are listed in Table 1.
8. The final LNG product is set to be slightly above ambient pressure, 1.2 bar

Table 1. Composition of Natural Gas and Mixed Refrigerant

Composition	Formula	Mole Fraction (%)	
		Natural gas	Mixed refrigerant
Methane	CH4	0.86	0.5
Ethane	C2H6	0.05	0.2
Propane	C3H8	0.03	0.15
i-Butane	C4H10	0.01	0
n-Butane	C4H10	0.01	0
Nitrogen	N2	0.02	0.15
Water	H_2O	0.02	0
TOTAL		**1**	**1**

Table 2. Simulation Initialization Parameters

Stream	Temperature (^{0}C)	Pressure (bar)	Vapour Fraction
Propane	15	20	0
Mixed Refrigerant	23	30	1
Natural gas	28	15	1

III. RESULTS AND DISCUSSION

Propane pre-cooling loop

The propane pre-cooling stage comprises of threehigh, middle and low pressures evaporators arranged in series, which allows a stage-wise cooling of the natural gas and mixed refrigerant.The evaporators are simulated in the steady state simulator as a combination of LNG Heat Exchangers and Separators arranged in series. This is done to enable multi-stream cooling and also separate the resultant vapour phase from the coolant stream after absorbing heat from the hot streams. The absorbed heat is used as latent heat of vaporization to convert the liquid phase to vapor phase while maintaining temperature.After the stage compressions, propane at a pressure of 20 bar and 115.7 Celsius is cooled and condensed using a seawater cooler to 15^{o}C.Prior to entering each evaporator, the propane gas is first throttled across a Joule-Thompson causing a corresponding temperature drop. This cold stream of propane is used to cool the natural gas stream and the mixed refrigerant stream in an LNG heat exchanger and the propane is then channelled to a phase separator where a small pressure drop occurs and the propane is spilt into liquid and vapor phase. The vapor phase is formed due to absorbed heat used as latent heat of vaporization by the propane stream.After phase separation, the vapor phase is sent for re-compression while the liquid phase is again, throttled across a Joule-Thompson valve to reduce the temperature and provide further cooling downstream. Table 3, 4 and 5 list the cooling, compressor stages as well as the heat and power requirements in the precooling block.

Table 3. Cooling stages in the precooling block

Stage	Pressure (bar)	\Temperature (Celsius)	\Vapour Phase after heat exchange
Initial	20	15	0
1	5.5	4.993	0.22
2	2.5	-19.34	0.13
3	1.1	-40.3	1

Table 4. Compression stages in the precooling block

Stage	Pressure (bar)
Initial	1.1
1	3.8
2	8
3	20

Table 5. Heat flow and power requirements in the precooling block

Unit	Heat flow (kJ/h)	Power (kW)
Turbine 1	22,631,943.09	6,287
Turbine 2	46,187,787.53	12,830
Turbine 3	71,853,232.87	19,960
Seawater cooler	366,979,843.62	-

Mixed-refrigerant loop

After propane precools the mixed refrigerant and natural gas to about -40^{o}C, the mixed refrigerant is sent to a separator where it is flashed into two streams, vapor and liquid streams referred to as the Light Mixed Refrigerant (LMR) and Heavy Mixed Refrigerant (HMR) streams, respectively. Due to this separation under pressure differential, the two new mixed-refrigerant streams have different composition as seen in the table 6. Table 6 shows that the LMR contains more of the light constituents like Methane and Nitrogen when compared to HMR which is mainly composed of heavier constituents like Ethane and Propane and a small percentage of Methane. This splitting is necessary to have enough refrigerants in the cold bundle of MCHE.

Table 6. Composition of LMR and HMR

Composition	Light MR (% mol fraction)	Heavy MR (% mol fraction)
Methane	0.63	0.20
Ethane	0.13	0.36
Propane	0.03	0.42
Nitrogen	0.21	0.02
TOTAL	1	1

<u>Warm Bundle and Cold Bundle</u>

In the warm bundle of the MCHE, the HMR is used to cooland liquefy the natural gas from an inlet temperature of -40^{o}C to -98^{o}C. The natural gas stream, LMR and HMR are cooled by the HMR stream, after it is throttled through a Joule-Thompson valve, from a pressure of 27.5 bar to 0.8 bar, thereafter, the temperature drops from -98^{o}C to -118.9^{o}C. It is commingled with the LMR stream coming back from the cold bundle of the

MCHE before heat exchange takes place. In the cold bundle, the LMR is used to liquefy and sub-cool the natural gas from a temperature of -98^oC to -158.2^oC. The natural gas stream and LMR stream are first cooled by the LMR stream, then the LMR stream is throttled across a Joule-Thompson valve, from a pressure of 27.5bar to 1 bar, and the corresponding temperature drops from -158^oC to -176.5^oC which provides cooling for the liquefaction and subcooling of the natural gas.After liquefaction of the natural gas, the LMR is commingled with the HMR stream after it has been throttled and the commingled stream is used for cooling in the warm bundle. This stream is then sent to the MR compressors for recycling through the propane precooling stage.

Compression of Mixed Refrigerant.

After the mixed refrigerant is used in the MCHE to liquefy and sub-cool natural gas, it is then sent for compression before it is reintroduced into the precooling block. The HMR and LMR are commingled before compression. At an inlet pressure of 0.8bar, the MR is compressed in two stages as seen in table 1 and table 2.

Table 7. Compression stages of the MR

Stages	Temperature (Celsius)	Pressure (bar)
Initial	-54.42	0.8
1	71.29	5
Cooling 1	20	5
2	162.9	30
Cooling 2	23	30

Table 8. Heat flow and Power requirements in the MR loop

Unit	Heat flow (kJ/h)	Power (kW)
Turbine 1	155,434,943.71	3,180
Seawater cooler 1	69,384,099.54	
Turbine 2	195,161,703.95	4,210
Seawater cooler 2	216,334,007.25	

Feed gas stream

The phase characteristics of NG compositions as presented in Fig.3, which indicate that where under the same pressure conditions, the NG with lower CH4 composition tend to have temperature range of two phases in the envelope relatively broader than the LNG with higher CH4 composition (see Fig. 4). These range of temperatures differences are very useful in controlling liquefaction and subcooling temperature.The phase characteristics of LNG compositions are presented in Fig.4., where under the same pressure conditions, the LNG with higher CH4 composition tend to have temperature range of two phases in the envelope narrower than NG with lower CH4 composition. These range of temperatures differences are very useful in controlling condensation temperature to liquefy and subcool LNG. In figure 4, you can observe a relatively smaller hooking effect of the dew point curve and a lower cricondentherm, attributable to the fact that the water and NGLs have been extracted from the feedgas stream. Table 9 shows the stage-based cooling of natural gas.

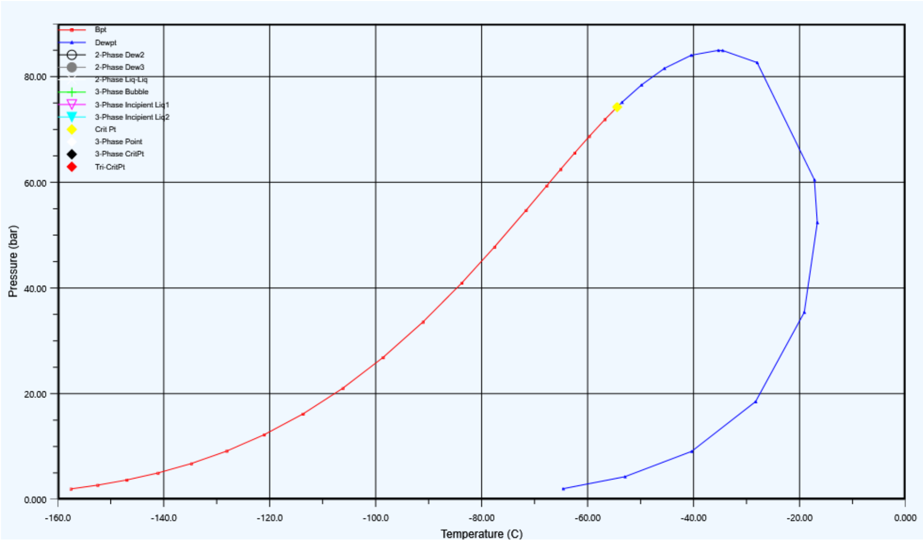

Fig. 3. Natural gas phase envelope before entering pre-cooling block

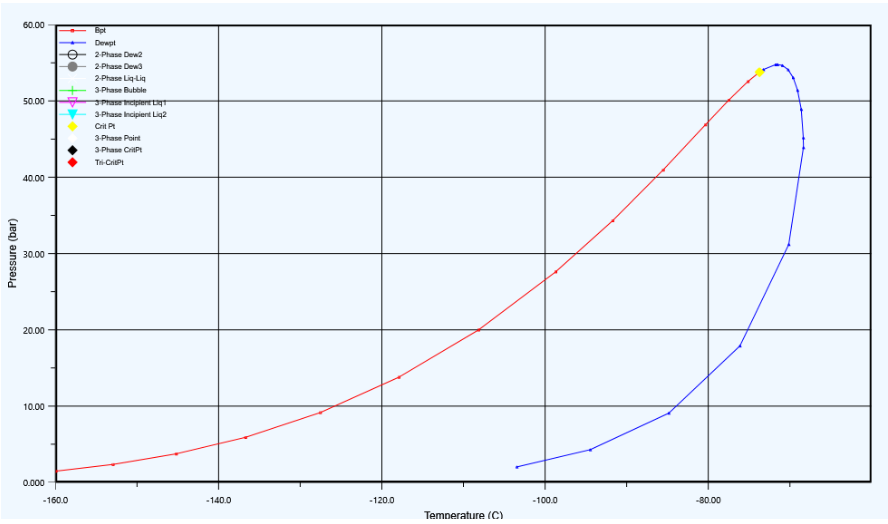

Fig. 4. LNG phase envelope after passing the precooling block.

Table 9. Cooling of NG in precooling block

Stage	Temperature (Celsius)	Pressure (bar)	Vapour Fraction
Initial	28	15	1
1st evaporator	5	15	0.98
Removal of Free water	4.7	14.5	1
2nd evaporator	-15	14.5	0.995
Removal of NGLs	-15	14	1
3rd evaporator	-40	14	1

The LNG exiting the MCHE passes through a flash separator, where the pressure is reduced to slightly above atmospheric pressure of 1.2bar which causes a corresponding temperature drop, thus subcooling the LNG to about -162.5 Celsius. The vapor that is flashing out due to this pressure drop can be used as fuel source, or processed to get refrigerant components which can be further utilized for various purposes.

Comparison of the single and dual compressor (i.e. double compressor) design of the MR loop

A variation of the base case (i.e. dual compressor MR cycle) is considered in this sub-section. In this variation, one compressor is used in the MR loop and the results of both simulations are compared to establish the relative technical performance of both MR cycles. Parameters were appropriately specified in order to avoid introducing any error in the simulation. The process performance of the dual compressor system can be represented in the composite curves of the warm and cold bundle shown in Figs. 5 and 6, respectively. In Fig. 5, the base C3-MR process warm bundle has a temperature difference of more than 32^{o}C between hot and cold composite curves. This implies that it has more room for energy improvement. The composite curves of C3-MR process cold bundle are shown in Fig. 7 where the composite curves of the base C3-MR process cold bundle have a dissimilar gap to the base C3-MR process warm bundle. The smaller temperature difference of composite curves in Fig. 6 suggests a relatively high thermodynamic efficiency This means that composite curves of C3-MR process cold bundlebrought the gap closer and, thus, getting higher efficiency of heat transfer (subcooling).

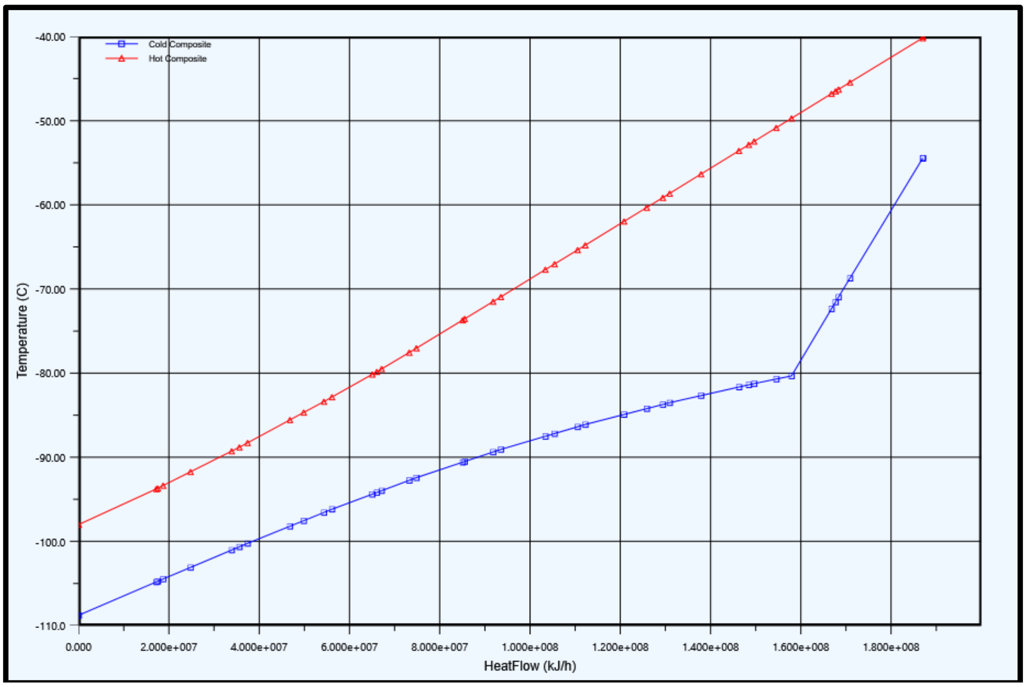

Fig. 5:The composite curve for the warm bundle in MCHE for 2 compressor model

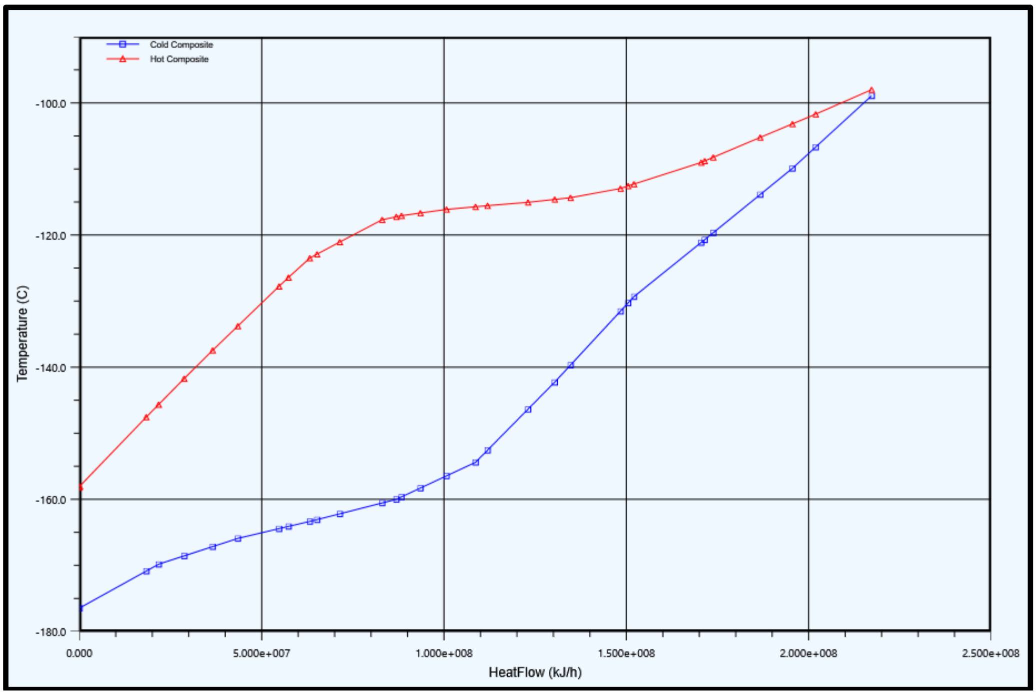

Fig. 6:The composite curve for the cold bundle in MCHE for 2 compressor model

You can observe from figures 5 and 6that the processes with subcooling has a smaller difference in temperature between the cold and hot composite curves compared to that of liquefaction, resulting in lower energy consumption. Thus, these composite curves reflects the efficiency of the dual compressor C3-MR process. The warm bundle composite curvesimply enhanced irreversibility, and will ultimately increase the refrigeration cost. To minimize the irreversibility, the gap between the composite curves must be minimized. Thus, the flow rates of the MR ingredients can be optimized to address the infeasibility/ irreversibility issue and to reduce the energy required during the liquefaction of natural gas. These variations ultimately yield to the optimal operational and design parameters for the warm bundle of the MCHE.

Further, we replaced the dual compressor MR system with a single compressor system and used the composite curves for the warm and cold bundles (see figs. 7 and 8) to ascertain if the C3-MR process can be optimized for comparison purposes. Clearly, we can observe from the composite curves of both figures that the single compressor system (modified case) is less thermodynamically efficient when compoared to the base case. There remains apparent improvements in the specific compression powers of the dual compressor system, leading to energy savings when compared to the modified case. Thus, the dual compressor process resulted in the greater improvement compared to modified approach, with a reduction in the specific compression power of 831.6 kWh/ ton-LNG being achieved, which is equivalent to an energy saving of 18% compared with the modified case.

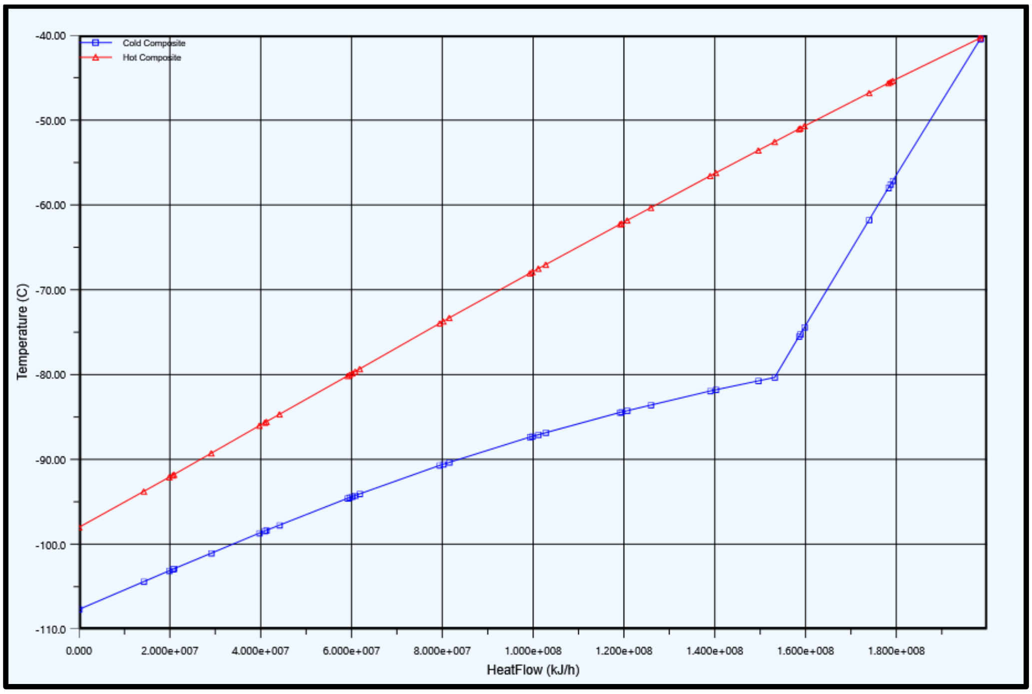

Fig. 7:The composite curve for the warm bundle in MCHE for 1 compressor model

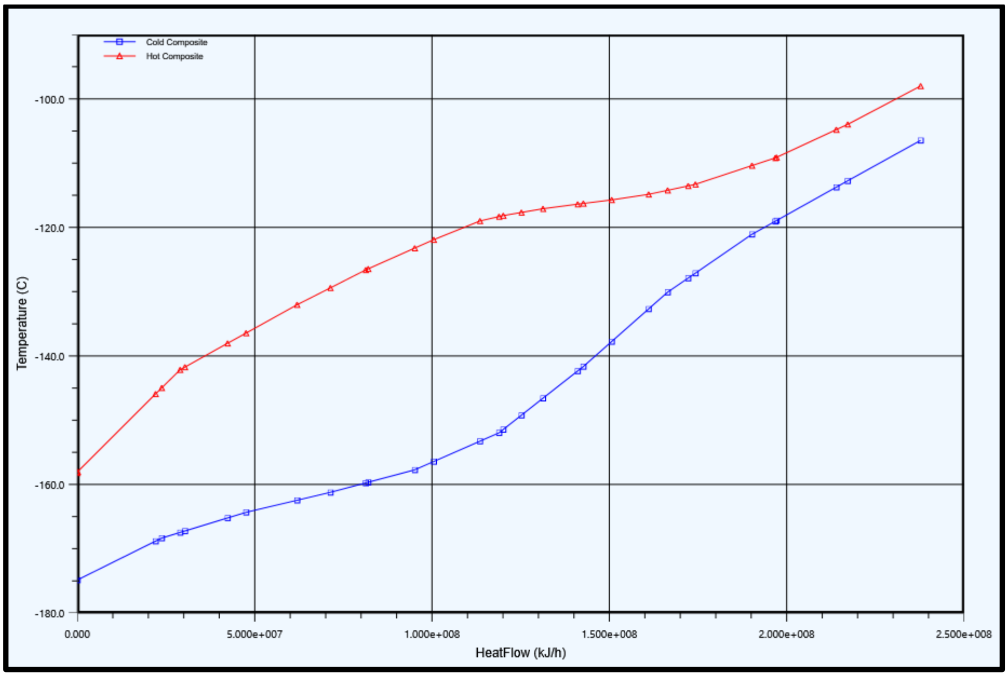

Fig. 8:The composite curve for the cold bundle in MCHE for 1 compressor model

Coefficient of Performance (COP)

Let us assess the results in terms of COP. The COP is the ratio of the heat taken out of the system by the coolers to the work input of the compressors.Replacing the dual compressor system with a single compressor system decreased the COP from 1.33 to 1.28 (see Figure 9). Thus, the base case is more efficient than the modified

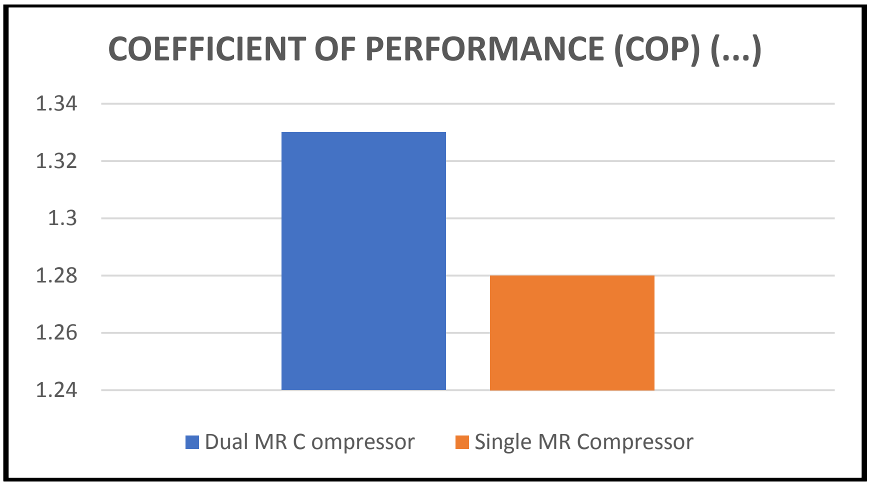

Fig. 9: Coefficient of Performance of the Dual and Single Compressor System.

case. The increase in COP is due to the increase in fluid subcooling before its flashing to the tanks. This increase in subcooling for the dual compressor system, is the result of the difference in flow rates performed by the heat exchange in the evaporators. Remember that the key role of the MCHE relates to the MR capacity for exchanging cold energy with an NG feed to produce the LNG product. We note that there is a higher cost for the dual compressor system. This higher investment of the dual compressor has an inverse relationship with energy cost in terms of the compression power, with the dual compressor case having a significantly higher energy efficiency in comparison with the modified case. The log mean temperature difference is a key parameter for COP optimization (though not covered in this paper).

Specific Power

Figure 10 shows the comparative performance of both the base and modified cases in terms of specific power. The specific power (W_s) is the work required to produce a unit mass of LNG. It is the ratio of the power consumed by the refrigerant compressors in kWto the amount of LNG produced in ton/hr (equation 1).

$$W_s = \frac{W_{comp}}{m_{LNG}} \qquad (1)$$

The dual compressor MR process reported a specific power of 831.59 KWh/ton LNG. The modified system implementing single compressor system reports a specific power of 981.27 KWh/ton.A summary of the comparison is tabulated in table 10.From the table 10, we can see that for the design to remain feasible which is

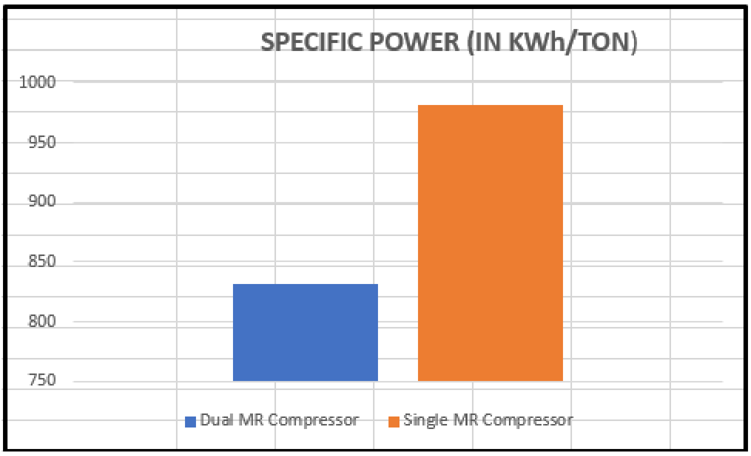

Fig. 10: Specific Power for the Dual and Single Compressor System

Table 10: comparison of different process parameters in C3MR design using one and two compressors

Property	Two compressors	One compressor	% Difference
COP	1.33	1.28	4%
Specific power (kWhr/ton)	831.59	981.27	18%
MR inlet pressure (bar)	30	15	50%
Total compressor duty (kW)	43,176.4 54,211.6 **Total = 97,388**	81,438.9	16%
Total turbine heat flow (kJ/h)	155,434,943.7 195,161,704.0 **Total = 350,596,647.7**	293,179,964.1	16%
Total cooler heat flow (kJ/h)	69384099.54 216334007.2 **Total = 285,718,106.8**	229,161,479	20%
LNG produced (mtpa)	1.393162	0.7961	43%

inherently limited by the maximum temperature in the mixed refrigerant loop after compression, the process parameters have to be adjusted accordingly. One compressor operating within somewhat safety limits, at an inlet pressure of 0.8 bar boost the MR pressure to 15 bars before it enters the propane precooling loop.The drop in the MR pressure affects the original design and there was need to make corresponding adjustment. In order to achieve convergence, the propane in circulation was reduced by 16% and natural gas entering the liquefaction unit was reduced by 28%. This change in parameter lead to a total production drop of about 43%. This is to say that the change in configuration from the base case to the modified case leads to a drop in LNG production by 43%. This is quite significant as it has a direct relationship with the economics of the project.

Another angle of comparison is the energy analysis. Energy requirement of the compressors has a direct relationship with the size of the turbines required to drive the compressors and invariably affects the economics. From the data above, we can see that the specific horse power in the model for two compressors is smaller than that of one compressor thus more energy savings. Also, the COP for the two-compressor model is higher than the COP of the one compressor model. The size of the energy requirements in the one compressor set-up is only 16% lower than the energy requirements of the set-up using two compressors. In conclusion, by changing the design from two compressors to one compressor in the MR loop, we saved cost by 16% but lost profit of 43%. This does not balance and in conclusion, the design containing two compressors is more technically and economically efficient that the design with one compressor.

IV. CONCLUSION

TwoC3-MR refrigeration cycles for LNG production were investigated in this work, based on structural modifications of the MR loop. These configurations are the dual compressor MR cycle, and the single compressorMR cycle. We studied their competitiveness, in terms of energy efficiency, with the benchmark process i.e. the dual compressor MR cycle as base case. The performance of the modified MR cycle was assessed with a case study of a real plant in Algeria for the production of LNG and compared against that of the benchmark process. The base case configuration was demonstrated to achieve shaft power savings of 18% against the modified MR cycle. The results revealed that replacing the dual compressor by a single compressor in the C3-MR LNG Process generally decreases the process performance as indicated by the increase in process thermal efficiency and LNG production besides the increase in plant total power consumption. The simulation model for both processes is built with the commercial steady state simulator. Compared with the two cases after optimization, it can be seen that the specific power of base case is smaller by 18% than that of modified case, and the COP is larger by 4% than modified case. This is in spite of the fact that the total compressor duty for base case and modified case are 97.381 kW and 81.438 kW, respectively. In conclusion, the base case shows better performance than that of modified case based on the energy efficiency analysis. The base case liquefaction process can continue to be used in baseload LNG plants with relatively low specific energy consumption.

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Emeka Joachin Okafor, et. al. "Investigation of the comparative performance of a modified propane precooled mixed refrigerant (C3-MR) natural gas liquefaction plant located in Algeria." *The International Journal of Engineering and Science (IJES)*, 12(2), (2023): pp. 32-43.