International Journal of Advances in Engineering and Management (IJAEM)
Volume 4, Issue 7 July 2022, pp: 1646-1652 www.ijaem.net ISSN: 2395-5252

Exo-Economic Analysis on the Liquefaction Unit of a Baseload LNG Plant

Tobechi F. Ozueh[1] , Joseph A. Ajienka[2], Ogbonna F. Joel[3]
[1]*Ph.D Candidate, African Center for Excellence, Center for Oilfield Chemicals Research (ACE-CEFOR), University of Port Harcourt, Port Harcourt, Rivers State, Nigeria.*
[2-3] *Professor, Department of Petroleum and Gas Engineering, University of Port Harcourt, Port Harcourt, Rivers State, Nigeria.*

Submitted: 15-07-2022 Revised: 27-07-2022 Accepted: 29-07-2022

ABSTRACT – Liquefying Natural Gas is an energy and cost intensive process and to this regard; this study was aimed to analyze five refrigerants in terms of energy requirement and cost, with consideration to maximize efficiency, minimize energy consumption, improve safety and profitability. An existing baseload plant was simulated using the proprietary simulation software, Aspen HYSYS V11.0 and the performance of our refrigerants – Nitrogen, Xenon, Argon and Krypton was analyzed and compared to the well-known APCI propane precooled mixed refrigerant (C3MR) Process. These results demonstrated that there are some comparative advantages of the three research refrigerant samples over the conventional, in terms of thermodynamic efficiency and coefficient of performance. Demonstrated therein, on the bases of cost; the presently used Mixed Refrigerant cycle poses to be more cost effective as compared to other refrigerants, but in close margin of 0.05 percent with Argon and the least cost effective being xenon. Their respective exergy efficiencies were in the order of; Argon (83%), krypton (82%), Nitrogen (65%), C3MR (63%), Xenon (36%) respectively.

KEYWORDS: Global Warming, Environment, Economics, LNG, Exergy, Coefficient of Performance, Costing, Simulation, Refrigerants, Liquefaction.

I. INTRODUCTION

Liquefied Natural Gas (LNG) company operations generally have both positive and negative effects on the environment and society. They provide an important commodity for domestic and industrial use. As a country industrializes and its economy becomes more sophisticated, the demand for gas for industrial and domestic use increases. These demands are met by the products from LNG plant the world over. LNG company operations also create benefits for local economies through job creation and service provision. The operation of LNG plants involves the extraction and transformation of natural resource with consequences for the environment and social conditions. They sometimes affect heritage and cultural resources and livelihoods in ways that generate conflicts, sometimes leading to violence. Thus, the location, design and operation of an LNG project are often the subject of government regulation worldwide [1] [2] [3]. In virtually all countries where LNG companies operate a plant or storage facility, there are legislations to ensure that the location, design and operation of such companies are done in a manner that results in minimal adverse impact to the natural and socioeconomic environment. These regulations normally would require a pre–operation impact assessment on the critical habitats of any endangered or at–risk species, and on human and institutional services. One precondition for a smooth operation of LNG plant therefore is to embark on an Environmental Impact Assessment (EIA). The environmental impact assessment usually involves detailed and extensive information pertaining to and characterizing the natural resources and environment of the project area, covering topography and climate, oceanographic conditions, land use, geology, hydrology; aquatic and terrestrial biology, air quality, noise, parks, marine reserves and protected areas, and cultural resources [2] [3].

LNG companies are expected not only to take precautionary measures; they are also expected to provide measures to mitigate some of the adverse effects of their operations. They are expected to address some of the dislocations and disruptions that may result thereof by direct intervention in the development of their host or affected communities. There is a broad range of intervention programmes undertaken by LNG companies worldwide, reflecting the various peculiarities of the contexts from the Balhaf LNG in Yemen, AES [5].

The onset of the liquefaction industry has witnessed the emergence of the propane precooled mixed refrigerant cycle (C_3-MR) as its preferred cycle due to its efficiency and performance. This cycle makes use of flammable organic refrigerants leading to the problem of safety [6]. Due to these issues, some questions arise such as: Are there inorganic refrigerants termed 'alternative refrigerants' which can successfully replace organic refrigerants refrigeration cycle? What are the economic and environmental implications of these 'alternative refrigerants? [7]
Based on the problems stated above, the software Aspen HYSYS version 11 was used to model the refrigeration section of the Liquefied Natural Gas plant compared to an alternative non-organic refrigerant while maintaining the existing design of the plant.

II. MATERIALS AND METHODS

A critical way of costing an equipment and process is by determining the work and energy utilized as well as the capacity of the major process equipment and exergy analysis. The coefficient of performance presents viable value to determine the costing.

2.1 Exergy Analysis of Refrigeration Processes

Exergy analysis was carried out to determine the entire process's energy consumption and process efficiency. The coefficient of performance (COP) is a quantitative metric that was used in this procedure. The Coefficient of Performance (COP) is a typical metric for measuring the efficiency of a cryogenic system. According to Equation 1, it is defined as the ratio of total heat evacuated by refrigerant to the amount of power needed by the system.

COP = Q/W (7)

where the nomenclature for the above equations are as follows: Q is refrigeration duty (MW); W is compressor power (MW), Σ W_{req} is the total compressor power required (MW) and $\dot{m}_{LNG}$ is the amount of LNG produced in tonne/h.

Exergy Analysis

Exergy or availability gives account of the amount of useful work that can be gotten out of a system at a specified state. It basically provides an answer on the question of how much useful work can be gotten from the energy which is actually available from an energy source. In this work, exergy analysis was used to determine the irreversibility that happens within the unit operations of the propane pre-cooling cycle, and the results are presented. In a system, the change in exergy (ΔEx) between the starting state and the end state is stated as follows:

$\Delta E_x = (H_o - H_i) - T_o (S_o - S_i)$

(8)

where T_o denotes the ambient temperature, H_o and S_o denote the enthalpy and entropy of the output stream, and Hi and Si denote the enthalpy and entropy of the intake stream, respectively. As the processing system progresses from its starting condition to its end state, the difference between the two properties will determine whether the system needs or creates work. If the exergy difference (Ex) is larger than zero, this indicates that the processing system is generating work, but if the exergy difference is less than zero, this shows that the processing system is requiring work from the outer system to achieve the state transition [4]. The exergy efficiency of a process is defined as the ratio between the total compressor power needed and the total energy lost divided by the entire amount of power required by the system (Eq.4). The exergy efficiency is denoted by the symbol:

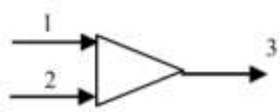
η_{ex} (%) =

(9)

where Σ W_{loss} is the total exergy loss work from each unit operation. The expressions to determine the exergy loss for all the unit operations in this study are summarized in Table 3.5.

2.2 Coefficient of Performance

Exergy loss calculation of various unit operations in propane cycle.



Mixer

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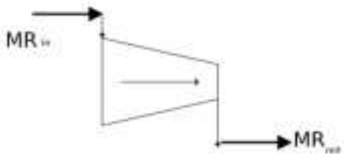
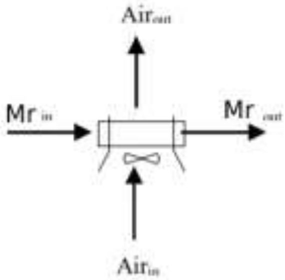
$Ex_{MIX,\ loss} = \dot{m}_1 e_1 + \dot{m}_2 e_2 - \dot{m}_3 e_3$ (10)



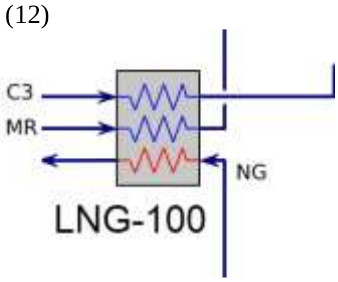
Compressor

$Ex_{COMP,\ loss} = \dot{m}(e_x i - ex_0) - W$ (11)



Air Cooler

$Ex_{AC,\ loss} = (\dot{m}_f e_f + \dot{m}_a e_a)_i - (\dot{m}_f e_f + \dot{m}_a e_a)_o$ (12)



LNG Heat Exchanger

$Ex_{HX,\ loss} = \dot{m} \sum exi - exo$ (13)

In the above equations, ṁ is the mass flow rate of propane at the inlet stream (kg/s), W is the compressor power (MW), S is the entropy (MJ/kg.K), ṁ a is the mass flow rate of air in (kg/s) and e is the specific exergy for the respective stream in (MJ/kg). Knowing these important process parameters for each process stream provides a better understanding of the changes occurring within the process. Hence, necessary adjustment can be done on the operating parameter to improve the process performance.

2.3 Costing Analysis of Refrigerants

The refrigerant costing is dependent on the price per kilogram and the total amount consumed in the process for the actualization of the required or specified LNG temperature.

The equation below was used throughout the analysis to determine the cost of each refrigerant used in the design.

Cost of refrigerant = cost/kg x quantity consumed

$R_{fc} = X/kg \times Q_c$ (14)

The cost was measured in United State dollar before conversion to Nigeria naira.

III. RESULTS AND DISCUSSION

Comparative cost analysis of Refrigerants is presented in Table 1 with details found in Appendix 1

Table 1: Comparative Cost Analysis for Refrigerant

Refrigeration Cycle	Total Cost for Refrigerants ($)
Mixed Refrigerants	55,271.02
Nitrogen	151,418.23

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Xenon	353,144,170.02
Argon	55,572.14
Krypton	36,314,340.09

Comparative analysis of Global Warming Potential of refrigerants are presented in Table 2.

Table 2: Global Warming Potential of refrigerants

Component	ASHRAE NO.	NET GWP - 100 Yrs
Methane	R-50	28
Ethane	R-170	5.5-10.2
Propane	R-290	3.3-9.5
Nitrogen	R-728	0
Argon	R-740	0
Neon	R-720	0
Krypton	R-784	0

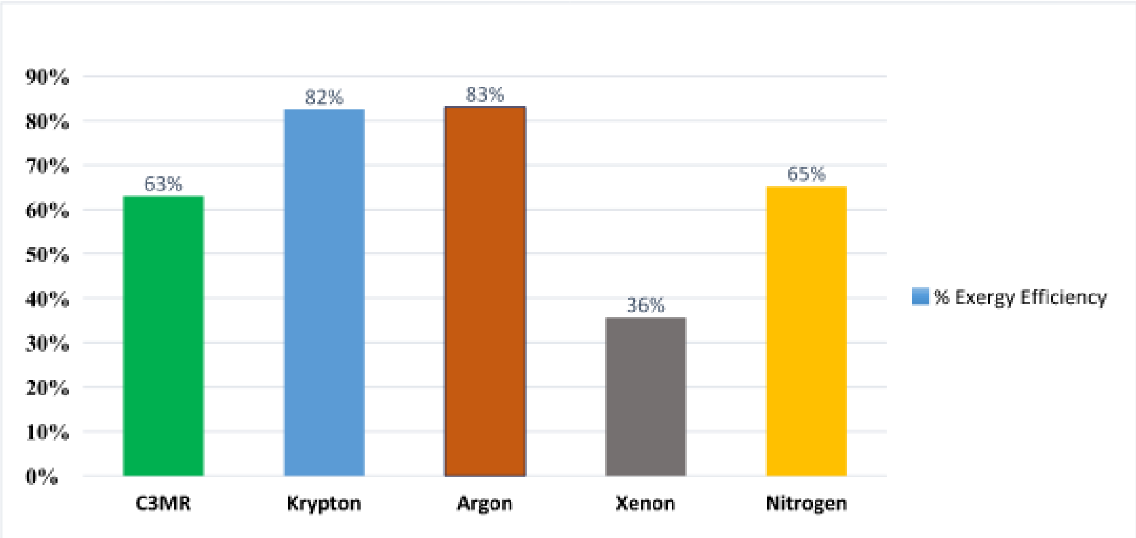

Fig. 1 Exergy Efficiency Comparison

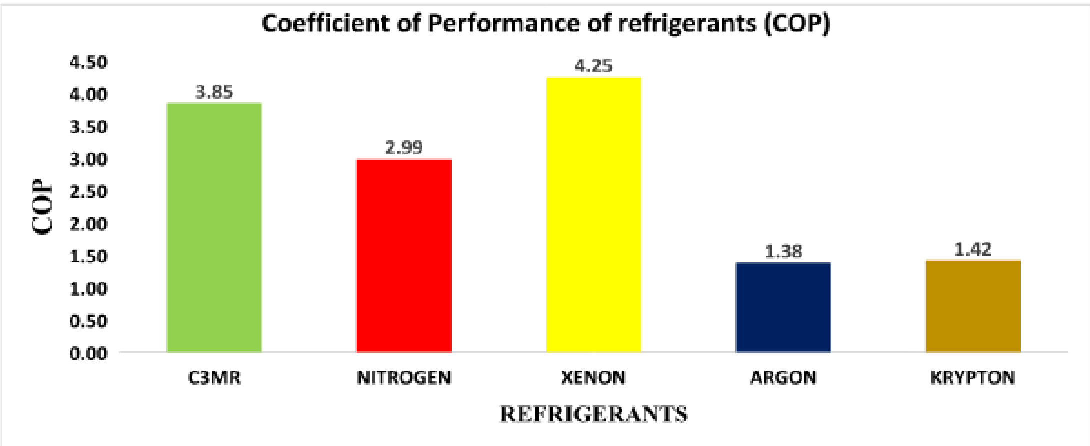

Fig. 2 Coefficient of Performance

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The cost of each refrigerant will determine its availability and readiness to use because it will affect and determine the profit margin after production and sales. From Table 1, the cost of the refrigerants obtained were analyzed. The most expensive refrigerants were Xenon and Krypton. Argon as a single refrigerant has a close cost to C_3MR. In Engineering research and innovation, health, safety, and environment are major factors to be considered. It is better expensive than destructive to the existence of mankind. In juxtaposing the net global warming potential, the non-hydrocarbons are preferred since they have no effect on the atmosphere. Global warming is a major problem to the world today.

IV. CONCLUSION

The performance of Argon, Nitrogen, Krypton and Xenon was analyzed and compared to the popularly used APCI propane pre-cooled mixed refrigerant C3MR in order to demonstrate their comparative advantage over the C3MR. This was done in terms of energy efficiency, exergy efficiency, coefficient of performance, global warming potential and cost. In cost comparison, xenon which is a good alternative due to its Coefficient of Performance, is not cost effective and this makes it not economically viable for most LNG process industries. The non-hydrocarbon refrigerants have zero global warming potential, and this makes them a better option in this critical time of global warming (environmental degradation). The highest energy efficiency was found with krypton and Argon.

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APPENDIX

Cost of Refrigerants

Table 2: Cost Analysis for Mixed Refrigerant

Cycle	Refrigerants	flowrate (Kg/hr)	Cost/kg ($)	Total amount spent ($)
MR	Nitrogen	8988.85394	3.57	32,090.21
	Methane	14324.4344	1.35	19,337.99
	Ethane	7421.6844	0.25	1,855.42
	Propane	1483.13449	1.34	1,987.40
	Total Amount			**55,271.02**

Table 3: Cost Analysis for Nitrogen Refrigerant

Cycle	Refrigerants	flowrate (Kg/hr)	Cost/kg ($)	Total amount spent ($)
	Nitrogen	41857.3746	3.57	149,430.83
NC	Propane	1483.13449	1.34	1,987.40
	Total Amount			**151,418.23**

Table 4: Cost Analysis for Xenon Refrigerant

Cycle	Refrigerants	flowrate (Kg/hr)	Cost/kg ($)	Total amount spent ($)
	Xenon	196190.101	1800	**353,142,182.62**
XC	Propane	1483.13449	1.34	**1,987.40**
	Total Amount			**353,144,170.02**

Table 5: Cost Analysis for Argon Refrigerant

Cycle	Refrigerants	flowrate (Kg/hr)	Cost/kg ($)	Total amount spent ($)
AC	Argon	59690.8024	0.931	55,572.14
	Propane	1483.13449	1.34	1,987.40
	Total Amount			**55,572.14**

Table 6: Cost Analysis for Krypton Refrigerant

Cycle	Refrigerants	flowrate (Kg/hr)	Cost/kg ($)	Total amount spent ($)
KC	Krypton	125215.009	290	36,312,352.69
	Propane	1483.13449	1.34	1,987.40
	Total Amount			**36,314,340.09**

Table 7: Comparative Cost Analysis for Refrigerant

Refrigeration Cycle	**Total Cost for Refrigerants ($)**
Mixed Refrigerants	55,271.02
Nitrogen	151,418.23
Xenon	353,144,170.02
Argon	55,572.14
Krypton	36,314,340.09

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Table 8: Comparison of the Energy Requirement of C3MR and Refrigerants (read directly from the simulation files)

UNIT OPERATION		C3MR	NITROGEN	XENON	ARGON	KRYPTON
		(kW)				
COMPRESSOR	K-1410	3316.576	3638.8704	4029.135	4052.621	4045.489
	K-1411	852.6901	321.35865	870.4512	918.1017	904.0871
	K-1411A	694.0079	287.68826	669.635	748.1729	725.6346
	K-100	132.6938	130.46547	130.3487	130.7978	130.0017
CHILLER	E-100	-6240.84	-4228.5755	7892.146	-2639.38	2685.554

Table 9: Exergy Analysis on the Main Cryogenic Heat Exchanger (MCHE)

		Inlet Streams								Outlet Streams											
		18.0		LP OVHD Gas EX C-1540		NG TO HEX				20.0		21.0		22.0							
Name	T0	$\dot{m}$	$\dot{s}$	$\dot{m}$	$\dot{s}$	$\dot{m}$	$\dot{s}$			$\dot{m}$	$\dot{s}$	$\dot{m}$	$\dot{s}$	$\dot{m}$	$\dot{s}$			$\sum_i \dot{m}_{i,in} S_{i,out}$	$\sum_i \dot{m}_{i,out} s_{i,in}$	$\Delta\dot{E}$	Unit
LNG-100	89.6	31895.9	6.5	166666.7	-1.3	672133.2	7.8			672133.2	7.6	166666.7	0.9	31895.9	3.7			5404343.4	5203255.9	200087.5	KJ/hr
		NG EX V-1401		21.0		22.0		43.0		24.0		25.0		26.0		44.0					
Name	T0	$\dot{m}$	$\dot{s}$	$\dot{m}$	$\dot{s}$	$\dot{m}$	$\dot{s}$	$\dot{m}$	$\dot{s}$	$\dot{m}$	$\dot{s}$	$\dot{m}$	$\dot{s}$	$\dot{m}$	$\dot{s}$	$\dot{m}$	$\dot{s}$	$\sum_i \dot{m}_{i,in} S_{i,out}$	$\sum_i \dot{m}_{i,out} s_{i,in}$	$\Delta\dot{E}$	Unit
LNG-101	-212.9	644891.2	7.8	166666.7	0.9	31895.9	3.7	31895.9	7.5	644891.2	5.2	166666.7	5.6	31895.9	4.0	31895.9	6.1	3873689.2	3048993.8	824695.3	KJ/hr
		24.0		26.0		31.0				LNG		30.0		32.0							
Name	T0	$\dot{m}$	$\dot{s}$	$\dot{m}$	$\dot{s}$	$\dot{m}$	$\dot{s}$			$\dot{m}$	$\dot{s}$	$\dot{m}$	$\dot{s}$	$\dot{m}$	$\dot{s}$			$\sum_i \dot{m}_{i,in} S_{i,out}$	$\sum_i \dot{m}_{i,out} s_{i,in}$	$\Delta\dot{E}$	Unit
LNG-102	3.1	644891.2	5.2	31895.9	4.0	31895.9	5.1			644891.2	5.1	31895.9	5.1	31895.9	5.5			3873835.2	3576788.8	297046.4	KJ/hr