REFERENCE TO THE EVALUATION OF LNG ENERGY APPLICATION AND PERFORMANCE

Engr. Nnadikwe Johnson[1], Engr. Ewelike Asterius Dozie[2], Ibe Raymond Obinna[3], iheme chigozie [4]

[1] *H.O.D in Department of Petroleum and Gas Engineering, Imo State University, Nigeria*

[2] *H.O.D in Agricultural Engineering, Imo State University, Nigeria*

[3] *Lecturer in department of Chemical Engineering, Imo State Polytechnic, Nigeria*

[4] *Imo state polytechnic , Nigeria*

ABSTRACT

Now, the quantity of LNG demand is steadily growing. The biggest drawback of LNG in compared to regular NG transportation is that it requires energy to liquefy LNG and subsequently some heat to re-gasify it. Regasification is often carried out with the loss of the low-temperature potential generated during LNG liquefaction. This potential may be used to generate energy in a variety of ways, including heat rejection from the thermodynamic cycle, which increases efficiency, preliminary pressurization of LNG by pump or thermal compression, and subsequent expansion in turbines, or a combination of these two processes. This article estimates the maximum work that can be gained by re-gasifying 1 kilogram of LNG using various techniques. The calculations suggest that heat rejection and thermal compression are the most efficient strategies.

Keywords: *cold energy, liquid natural gas, regasification, exergy*

---

1. INTRODUCTION

The concept of using cryogenic fluids to generate cold energy has gained widespread recognition in recent years [1-3]. It is primarily due to rising LNG production volumes, a general trend toward energy conservation, and the energy potential stored in cryogenic fluids being used to offset the energy consumed during liquefaction.

During conventional LNG re-gasification (which in most cases utilizes ambient or waste heat), the working fluid loses its low-temperature potential when it reaches the ambient temperature. When pressures are also equal, compressed gas's potential energy is likewise lost.

The primary methods for harnessing LNG's energy potential are as follows:

✓ Utilization of cryogenic working fluid as a low-temperature source in direct cycle converters for heat rejection Q_2.

✓ Thermal compression is used during LNG re-gasification, with the high-pressure gas then used in expansion machines to generate electricity. x Combined schemes incorporating the first and second cases.

✓ In all cases, it is assumed that LNG is delivered to a consumer in a gaseous state with specified pressure and temperature parameters.

During the method selection and development of the LNG energy potential method and plant for additional energy generation, the issue of thermodynamic efficiency and comparative assessment of such energy plants, as well as the limited capabilities of LNG as a low heat source and working fluid, became relevant.

2. REGASIFICATION WITH CRYOGENIC WORKING FLUID COLD ENERGY UTILIZING IN A CARNOT CYCLE

Consider a hypothetical energy plant (Fig. 1) that operates on a direct Carnot cycle within the temperature constraints imposed by the cryogenic working fluid (lower source) and the surrounding environment (high source). When the temperature head between the working fluid and the heat source is equal to zero, only phase change heat is used on the 1-4 branch; on the 4-5 branch, physical heat from the gas's changing temperature Tci is used in each elemental Carnot cycle.

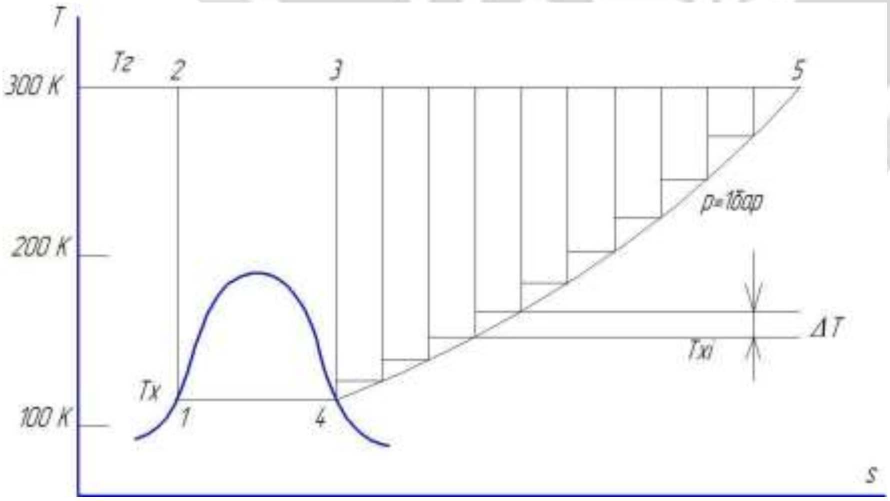

Fig. 1: About calculation of maximal work generated in the cycle during cycle heat rejection to cryogenic fluid.

With provided assumptions the work in the 1-2-3-4 cycle for 1 kg of LNG can be determined as:

$L = Q_1 - Q_2$

Rejected heat Q_2 per 1 kg of LNG will be fixed value for given parameters of cryogenic fluid $Q_2 = m.r = 1.510 = 510$ kJ/kg.

Considering, that for Carnot cycle: $\eta_{Carnot} = 1 - T_c / T_h = 1 - Q_2 / Q_1$

where Q_1 – added heat:

$$Q_1 = Q_2 \cdot T_h / T_c .$$

Then the work of the cycle will be equal to:

$$L = Q_2 \left(T_h / T_c - 1 \right).$$

On branch 4-5 work for every elemental Carnot cycle will be determined by similar relation:

$$dL_i = dQ_1 - dQ_2 = dQ_2 \left(T_h / T_{ci} - 1 \right).$$

Available heat (cold energy of cryogenic fluid) rejected from elemental cycle is calculated as:

$$dQ_2 = m_{LNG} c_{pci} dT_{ci} .$$

The work performed by the 4-3-5-4 cycle can be calculated as the sum of the work performed by the elemental Carnot cycles, but in extreme cases, it will correspond to the work performed by this cycle with heat added in isothermal process 3-5 and heat rejected in isobaric process 5-4.

The calculation results indicate that the theoretical work performed by the 1-2-5-4-1 cycle per kilogram of LNG is 1093-1146 kJ. If a different heat source is used (rather than the ambient), the cycle work and thermal coefficient of performance will change proportionately (Fig. 2).

Thus, theoretical characteristics indicate that no energy system capable of generating electricity and utilizing LNG cold energy can generate more work or have a higher COP than the values described above.

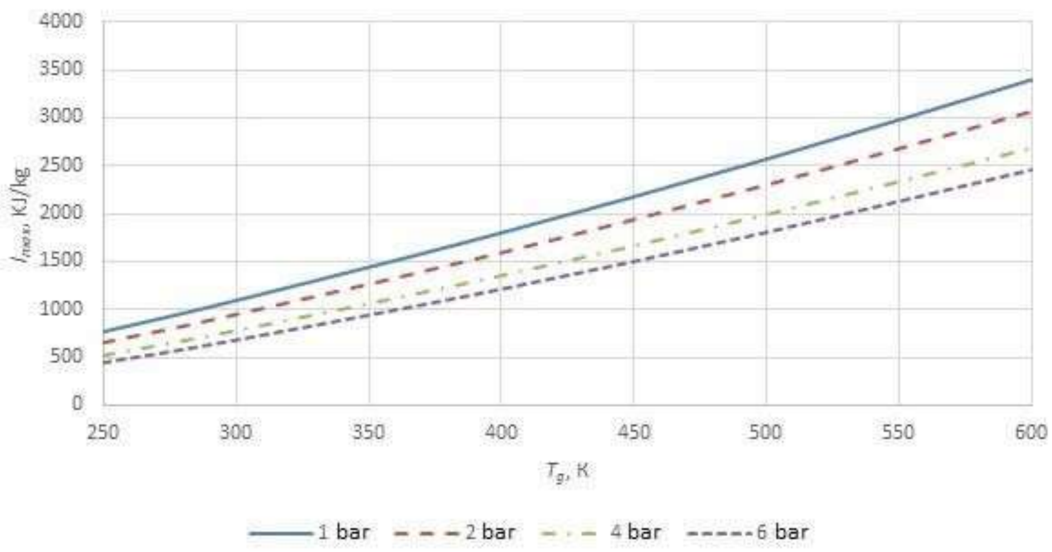

Fig. 2: Dependency of the maximal specific work generated by 1-2-5-4-1 cycle with cycle heat rejection in to cryogenic fluid from heat source temperature and LNG pressure.

3. RE-GASIFICATION WITH PRELIMINARY PRESSURE RISING

Additional work can be generated during the re-gasification process not only by utilizing the cold energy of cryogenic fluid as a heat sink, but also by the work produced by cryogenic fluid itself. To do this, it is required to increase its pressure. There are two primary techniques for raising the pressure in cryogenic fluids: increasing the pressure in pumps while the cryogenic working fluid is still in the liquid state, and thermal compression. In such plants, electric energy is generated via expansion turbines.

Thermodynamic examination of such plants demonstrates that work is produced via the establishment of an open Rankine cycle. Indeed, the cryogenic fluid pumping process of gasification comprises of the following stages (see Fig. 3): pumping cryogenic fluid into the gasifier (process 1-2), where evaporation and vapor overheating occur; (processes 2-3 and 3-4).

Due to its almost negligible value in comparison to generated work or added heat, work spent on the pump drive is frequently overlooked during preliminary calculations. Then, enlargement of energy-generating turbines occurs (process 4-5). The parameters in point 5 are proportional to the expansion ratio. If the temperature of the working fluid remains higher than the ambient temperature after expansion and the pressure of the working fluid remains greater than the ambient pressure, the working fluid can be heated to the temperature of the hot heat source and then expanded again in the second turbine. It is self-evident that multi-stage expansion may be employed in situations where the turbine number selection is an optimization problem. This goal was accomplished in [4], which demonstrated that an optimized plant is capable of achieving a 90 percent expansion efficiency.

There is a possibility that the cycle work of the plant (Fig. 4) will increase. To increase the amount of work performed, it is required to raise the pressure applied by the cryogenic pump. Assuming there are no restrictions on higher pressure values (which do exist [5]), it is feasible to see that cycle work is also greatly enhanced. However, energy consumption for pump drive is increased, and this must be included into the energy balance.

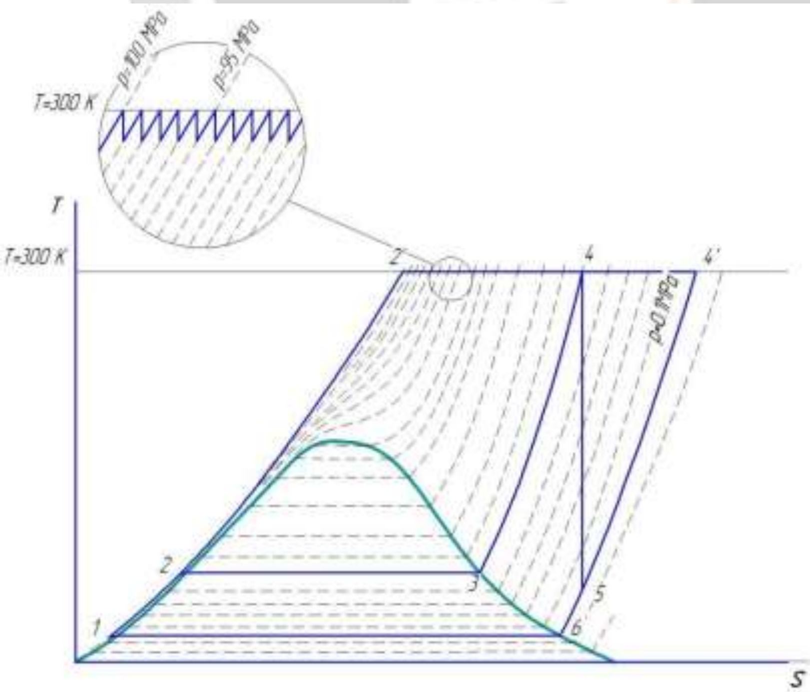

Fig. 3: About calculation of maximal cycle work during cryogenic product pressurizing.

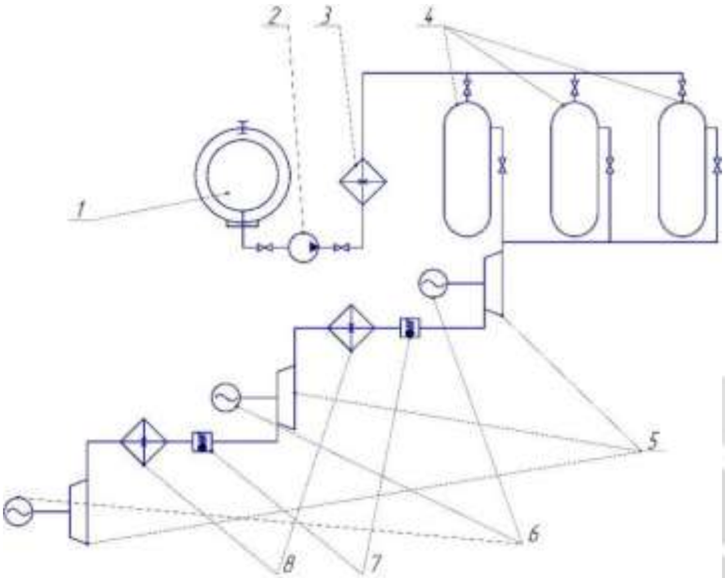

Fig. 4: Scheme of plant for LNG regasification with preliminary cryogenic fluid pressure increase

1 – LNG storage tank; 2 – pump; 3 – evaporator; 4 – tanks for the storage of evaporated cryogenic products; 5 – turbines; 6 – power generators; 7 – gas reducers; 8 – heaters.

The cycle's theoretical maximum work is accomplished by an unlimited number of turbines with intermediate heating of the working fluid that corresponds to the isothermal process 2'- 4'. The calculations (Fig.5) demonstrate that with an asymptotic useful work function of pressure and a nearly linear function of energy needed for pump drive, there is a definite maximum at 65 MPa and 853.3 kJ/kg.

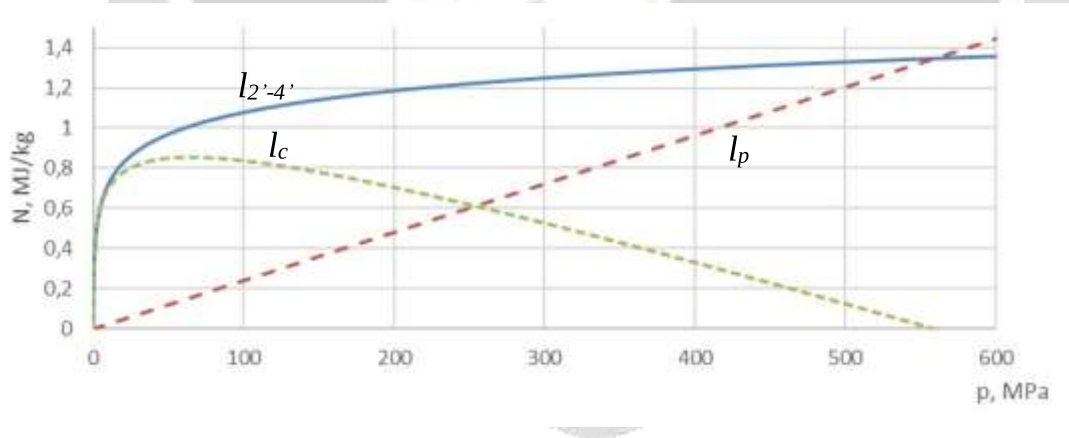

Fig. 5: Cycle work, required pump power and effective power output in cycle on maximal cycle pressure.

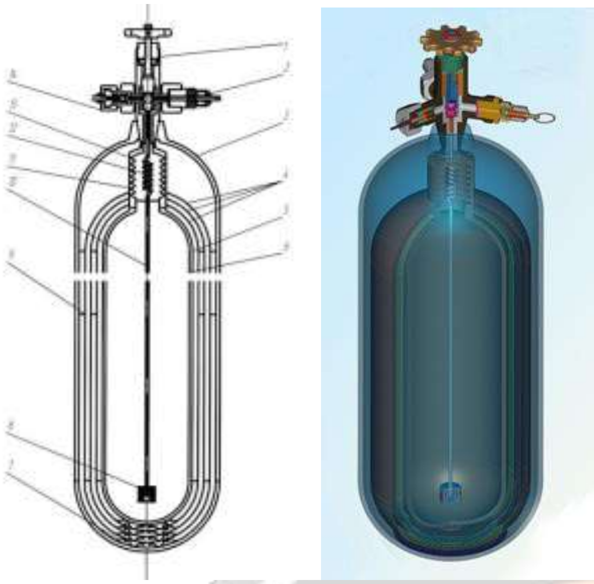

Fig. 6: Design of tank suited for thermal compression

1–valve; 2–safety valve; 3–tank; 4–screens; 5–heat insulation; 6–Dewar vessel; 7–compressive plate; 8–filter; 9–amortizing fitting; 10–intake tube; 11–bellows; 12–serpentine; 13–barrel; 14–filler connection [7].

The amount of heat supplied in steps 2-4' is defined by the equation:

$$q_1 = l_{2'-4'} = RT \ln\left(p_{2'} / p_{4'} \right),$$

rejected heat is cold energy of 1 kg of LNG:

$$q_2 = i_{4'} - i_1.$$

Required pump drive power:

$$l_p = i_{2'} - i_1,$$

useful cycle work (without required pump drive power):

$$l_c = l_{2'-4'} - l_p.$$

Calculations for LNG indicate that when appropriate cycle pressure is considered (see Fig. 3) and expansion to a pressure of point 4' is considered, usable cycle work equals 850 kJ/kg and may be higher depending on the temperature of the high heat source (Fig. 6).

Consider thermal compression in a tank with a closed volume. It might be a natural process of re-gasification caused by heat fluxes through the walls [6] or an external heat exchanger linked only to the tank. Figure 6 illustrates an example of such a tank. In most circumstances, regasification in an external heat exchanger is preferable [7] because the process is simpler to regulate and the time required for regasification and gas heating is greatly decreased. In the proposed tank re-gasifier, the mass of cryogenic product packed in the inner volume of the tank does not equal the capacity of the whole tank and is dictated by the pressure condition in the tank's ultimate state. Consider the possibility of a tank that is capable of withstanding a pressure of gasified cryogenic product that completely fills the tank's capacity. Obviously, this pressure will be maximum.

The mass of the filled liquid is determined by the volume of liquid equal to the tank volume:

$$m_l = \rho_l V.$$

We can calculate the pressure of a liquid (for example, LNG) based on its density and ultimate temperature. This value is 320 MPa for LNG.

This number demonstrates that thermal compression can achieve a greater pressure than mechanical compression. This indicates that with thermal compression induced by ambient or waste heat, more useful work may be accomplished than through mechanical compression caused by isothermal expansion:

$$N_{tc} = RT \ln \frac{p_1}{p_2} = 519.6 \cdot 300 \cdot \ln \frac{320}{0.1} = 1.258 MJ.$$

Simultaneously, developing a tank capable of withstanding pressures of up to 320 MPa is challenging. Even if such tanks are created, their capacity will be restricted to 50...70 MPa.

These circumstances are identical to those described before for cryogenic product pumping. Given that when a tank is emptied, its pressure decreases and usable work is created, a thermal compression system may be less efficient than pumping.

Thus, early research indicates that the maximum values of acquired work and its efficiency are comparable for cryogenic product pumping and thermal compression systems.

4. COMBINING OF CYCLES WITH PRELIMINARY PRESSURE INCREASE AND THAT REJECTION TO CRYOGENIC PRODUCT

Additionally, the aforementioned techniques of using LNG cold energy may be combined. In such facilities, heat is rejected from the cycle and converted to a cryogenic product with a pre-increased pressure. Initially, such plants are used in cycles that necessitate the application of working fluids with a higher saturation temperature. Fig. 7 illustrates a plant that employs the Rankine cycle with a preparatory pressure rise.

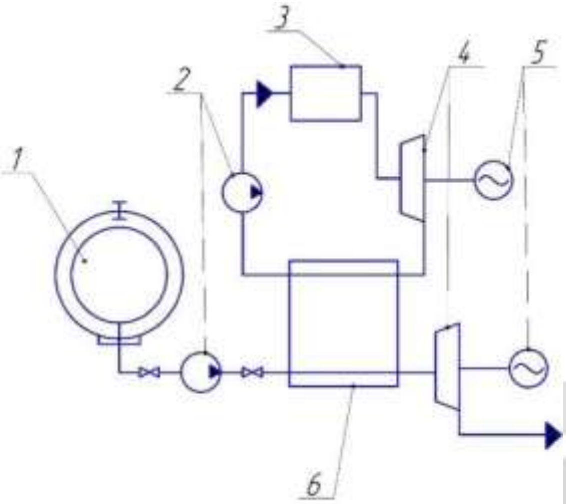

Fig.7: Regasification facility using a combination of preparatory pressure increase and heat rejection from the Rankine cycle to produce a cryogenic product: 1 – LNG tank; 2 – pumps; 3 – evaporator; 4 – turbines; 5 – producers of power; 6 – evaporator-condenser.

The whole work output of such a facility will be characterized as two types of work: closed cycle work and cryogenic product expansion work. In the extreme instance, work created by the plant outlined in Chapter 2 and work received via cryogenic product expansion will be summarized.:

$$l = l_{2-2'-4-3-2} + l_{4-4'} - l_{1-2} \quad ,$$

The processes will be as shown in Figure 3, with 1-2 indicating pressure rise of the cryogenic product through pump, 4 indicating isothermal expansion of the re-gasified cryogenic product, and 2-2'-4-3-2 indicating the cycle outlined in Chapter 2. The cycle calculation expressions are shown above.

For instance, if the initial pressure is increased to 0.6 MPa, the maximum work that may be gained through heat rejection from the cycle to cryogenic product is 676.1 kJ/kg (Fig.2).

Isothermal expansion work from 0.6 to 0.1 MPa at 300 K is equivalent to 279.3 kJ/kg, whereas pump drive work is equal to 1.1 kJ/kg. Thus, the total work produced by such a cycle is 954.3 kJ/kg when the power required for pump drive is included. It enables the conclusion that the thermodynamic combined technique is less successful than pressurizing heat rejection. It may, however, be considered when building a plant that uses working fluids with a relatively high saturation temperature.

5. CRYOGENIC PRODUCT USE EFFICIENCY CRITERIA

The findings of this study provide a guideline for estimating the efficiency of energy plants and systems suitable for energy production during cryogenic product regasification. The most straightforward and physically comprehensible criteria is the relationship between the amount of work performed and the mass unit of cryogenic product:

$$l_{sp} = \frac{N}{G}\frac{kJ}{kg}.$$

where N denotes the plant's power output and G denotes the rate of cryogenic product flow.

The given criteria may be used to compare plants that operate at the same temperature level. The second criteria is the efficiency of energy creation during regasification, which is dependent on the kind of heat source (or its temperature), which may be ambient, waste heat, or specific heat sources such as solar energy.

$$\eta_{reg} = \frac{l_{sp}}{l_{max}},$$

where l_{sp} denotes the specific work performed by a particular plant (design or actual values), and lmax is the maximum amount of work possible with the current scheme.

The offered criteria quantifies the perfection of any form of regasification's energy generating process. The values of maximum specific work are computed in this section as a function of the working fluid and the thermodynamic conditions of its storage (for methane held at 0.1 MPa and 112 K, the values of maximal work are shown in table 1). The third criteria is relative coefficient of performance (COP), which is the ratio of the thermal coefficient of performance of a proposed or existing energy plant to the maximum thermal coefficient of performance:

$$\overline{\eta} = \frac{\eta_{th}}{\eta_c}.$$

This criteria quantifies the thermodynamic perfection of the energy generating process when a cryogenic product is used to generate cold energy.

Table 1: Characteristics of the different methods of cryogenic product cold energy utilizing.

Method of cryogenic product cold energy utilizing	Maximal specific work lmax, kJ/kg	Maximal pressure of cryogenic product Pmax, MPa	Features
Utilizing a cryogenic product as a heat sink in thermodynamic cycles	1093-1146	0.1	Necessity of heat engine application
Pressurizing by pump use	853.3	65	Necessity to use pumps and turbines
Thermal compression during regasification	1258	320	Necessity to use high-pressure tanks and turbines

For the purpose of estimating the energy potential of cryogenic products at low temperatures, it will also be beneficial to include a criteria that defines the amount of energy that can be recovered from the amount of energy used during cryogenic product liquefaction. The average amount of energy used during LNG liquefaction is 1200 kWh. The recovered energy coefficient may be computed as follows:

$$k_r = \frac{N}{W_\Sigma}.$$

Additional criteria may include the values of added Q1 and rejected Q2 heat, the maximum pressures in cycles, the temperature and pressure of the cryogenic product being used, the characteristics of the high heat source, and the surrounding environment.

6. CONCLUSION

The study described in this paper is intended to offer broad estimating methodologies for energy plants that employ cryogenic fluids to generate cold energy. Several methods of energy creation were selected for investigation and comparison during cryogenic product regasification: exploiting cold energy to reject heat from the thermodynamic cycle; increasing the cryogenic fluid pressure with subsequent expansion and energy generation; and a combination of both. Calculations indicate that the ideal technique to use the cold energy of a cryogenic product in the extreme situation is by thermal compression in a confined container followed by additional expansion. However, this procedure needs special fuel tanks capable of withstanding pressures of up to 320 MPa, which is not conceivable at the present state of science and technology development. When thermal compression is applied to levels that are within present technological capabilities, the quantity of work created is almost identical to that generated by mechanical compression through a pump.

Utilizing cryogenic products as a source of low heat provides a number of advantages. The provided work calculation is for an extreme situation with an unlimited number of Carnot cycles at each temperature level. Indeed, contemporary advancements include up to three cascades [8], necessitating the solution of an optimization issue in which pressure, temperature, and the composition of the working fluid are all variables and the optimization goals are maximum work production and least cost.

Additionally, criteria for estimating the thermodynamic perfection of the energy production process as well as comparing similar type plants operating at similar temperatures and pressures were proposed. Comparative analyses of plants that employ a variety of pressure and temperature levels from a high source to utilize the cryogenic product's cold energy demand additional exploration.

ACKNOWLEDGEMENTS

The Authors are thankful to, IMO state university, Owerri Nigeria for Enabling the Research project.

REFERENCES

[1] J. Wang, J. Wang, Y. Dai, P. Zhao. Thermodynamic analysis and optimization of a transcritical CO2 geothermal power generation system based on the cold energy utilization of LNG, Applied Thermal Engineering Volume 70, Issue 1, 5 September 2014, Pages 531-540.

[2] H. Sun, H. Zhu, F. Liu, H. Ding, Simulation and optimization of a novel Rankine power cycle for recovering cold energy from liquefied natural gas using a mixed working fluid, Energy Volume 70, 1 June 2014, Pages 317-324.

[3] M.R. Gómez, R.F. Garcia, J.R. Gómez, J.C. Carril. Thermodynamic analysis of a Brayton cycle and Rankine cycle arranged in series exploiting the cold exergy of LNG (liquefied natural gas), Energy Volume 66, 1 March 2014, Pages 927-937

[4] E.V. Blagin, A.I. Dovgyallo, S.O. Nekrasova, D.V. Sarmin, D.A. Uglanov. Estimation of the energy efficiency of cryogenic filled tank using in different system and devices. Applied Thermal Engineering, 2016. doi: 10.1016/j.applthermaleng.2015.09.052.

[5] V.N. Novotelnov, A.D. Suslov, V.B. Poltaraus. Cryogenic machines. Politehnika, Saint-Petersburg, 1991.

[6] A.I. Dovgjallo, D.V. Sarmin, D.A. Uglanov. Preliminary tests of tank with cryogenic charging for onboard throttle system of cooling. SSAU reporter, 3(27) (2011) 78-84.

[7] T.V. Ashihmina, D.V. Sarmin, D.A. Uglanov. Using a high-pressure vessel with cryogenic refuelling as a storage regasifier for autonomous complexes of gas supplyng and railway transport. SSAU reporter. 5(29) 2011. 21-28.

[8] F. Xue, Y. Chen, Y. Ju. A review of cryogenic power generation cycles with liquefied natural gas cold energy utilization. Frontiers in Energy. 25 January 2016, Pages 1-12.