A Review on Power Generation and Feasibility of Cryogenics (LN_2)

Rashitha Kumari U[1]and Prabhanj S R[2]
[1]*Asst. Professor, Chemistry Department, Shivaji College of Engineering,*
[2]*Mechanical department, Sri Eshwar College of Engineering, Coimbatore*

Abstract **- In this paper we will discuss about the possibilities and application of usage of cryogenics in the field of power generation in power plants. This paper signifies the importance of switching to a cleaner fuel and why liquid nitrogen is chosen over other cryogenics. This paper also explains how traditional powerplants can be converted to liquid nitrogen powerplants and how it can be made efficient overtime.**

I. INTRODUCTION

The foundation of our energy infrastructure, power plants produce the electricity needed to run our cities, businesses, and residences. But the environment pays a price for their practices. Let's examine how power plants affect the environment and the pressing need for cleaner fuels to serve as a long-term substitute. Particulate matter, sulfur dioxide (SO_2), and nitrogen oxides (NO_x) are among the pollutants released by power plants. These are linked to respiratory illnesses, acid rain, and smog.

Research commissioned by the Centre for Liquefied Natural Gas (CLNG) found that the life cycle emissions of domestic coal power plants in the United States now are 2.5 times higher than those of LN. One of the main greenhouse gases released by fossil fuel-based power plants is carbon dioxide (CO_2). This modifies weather patterns and intensifies global warming.

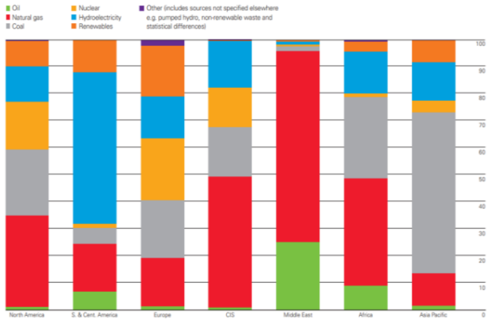


Figure 1: Global energy generation resources [5]

When US LNG or imported, pipelined gas is used to generate electricity, greenhouse gas emissions are typically 50.5% fewer than when coal-based electricity is used. Water is used in thermal power plants for cooling, which can damage aquatic ecosystems and cause thermal pollution. In this paper we can see the use of liquid Nitrogen in place of water to run a powerplant.

II. PROPERTIES OF NITROGEN AS GAS

The chemical element nitrogen has the atomic number seven and the symbol N. The lightest element in group 15 of the periodic table and a nonmetal is nitrogen. N2 is the most prevalent element in air without a compound, making up approximately 78% of the Earth's atmosphere. Nitrogen is comparatively rare in the solid portions of the Earth due to the volatile nature of nitrogen molecules. The typical method for producing elemental nitrogen from air is pressure swing technique of adsorption. The majority of elemental nitrogen generated commercially is used as liquid nitrogen in cryogenic applications, with the remaining portion being used as an inert (oxygen-free) gas for commercial purposes including food packaging.

Liquid nitrogen, being a cryogenic liquid, can be hazardous as it can burn skin when it comes into touch with the cold, however for brief periods of time (less than a second), the Leiden frost effect offers protection.[106] Liquid nitrogen consumption can seriously harm internal organs.

III. PROPERTIES OF LIQUID NITROGEN

Liquid nitrogen has a boiling point of approximately -196°C (−321°F; 77 K) and freezes at -210°C (−346°F; 63 K). It is produced industrially by fractional distillation of liquid air. The diatomic character of the N_2 molecule is retained after liquefaction.

Weak van der Waals interactions between N_2 molecules result in little interatomic attraction, contributing to nitrogen’s unusually low boiling point. Liquid nitrogen rapidly freezes living tissue, so thermal insulation is necessary during handling and storage.

It can be stored and transported in vacuum flasks, with holding times ranging from hours to weeks. Liquid nitrogen can reduce the oxygen concentration in the air, acting as an asphyxiant, especially in confined spaces.

The liquid-to-gas expansion ratio of nitrogen is 1:694 at 20°C (68°F). This means that liquid nitrogen boils rapidly to fill a volume with nitrogen gas when it vaporizes. The most affordable, widely produced, and typical cryogenic liquid is liquid nitrogen. Air liquefaction facilities produce it in large quantities. Normal liquefaction involves passing ambient air through a dust precipitator and pre-cooling it using standard refrigeration methods. It is a pretty straightforward procedure. After that, it is compressed to roughly 100 atmospheres inside of huge turbo pumps. The air is allowed to rapidly expand through a nozzle and into an insulted chamber once it has reached 100 atmospheres and cooled to ambient temperature. After a few cycles, the chamber's temperature drops to the point where air entering it begins to liquefy.

IV. PROPOSED SCHEME

The proposed schemes aim is to produce energy using liquid nitrogen (LN_2) with the process of Rankine cycle. It also explains the preparation and storage of liquid nitrogen before expansion.

IV. POWER GENERATION USING LIQUID NITROGEN

The process of Rankine cycle is used in the process of power generation in thermal powerplants.

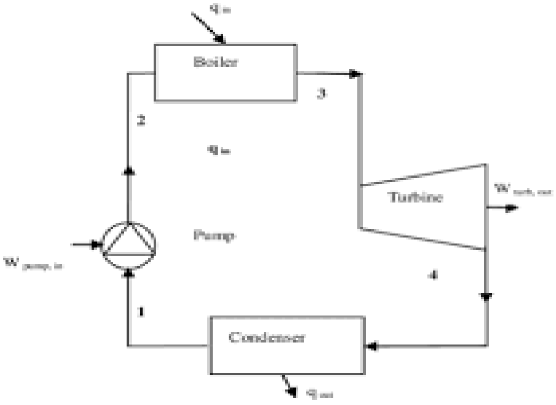


Figure 2: Rankine Cycle [6]

The Rankine cycle is a fundamental thermodynamic process that underpins a significant portion of global electricity generation. It's a closed loop system that converts heat energy into mechanical work, which can be used to produce electricity. Here's a detailed breakdown of the Rankine cycle [7]:

a. Isentropic Expansion (State 1 to 2): High-pressure, high-temperature steam (state 1) enters the turbine and expands adiabatically (without heat transfer) through the turbine blades. This expansion increases the velocity of the steam, converting its thermal energy into kinetic energy. As the steam's velocity increases, its pressure and temperature decrease (state 2). In an ideal Rankine cycle, this expansion is isentropic, meaning there is no entropy change (isentropic process).

b. Constant Pressure Heat Rejection (State 2 to 3): The low-pressure steam exiting the turbine enters the condenser. In the condenser, heat is transferred from the steam to a coolant, typically circulating water, at a constant pressure. This constant pressure process condenses the steam into a low-pressure liquid state (state 3).

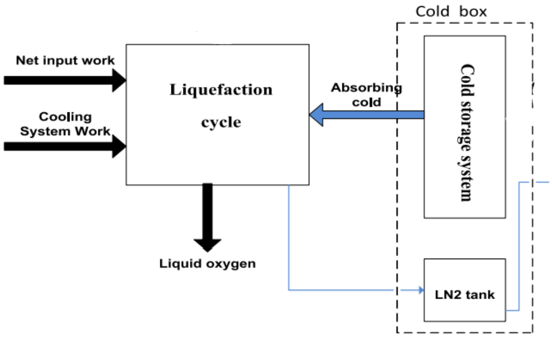
c. Isentropic Pumping (State 3 to 4): The condensed liquid water exiting the condenser is fed into the pump. The pump increases the pressure of the water adiabatically (state 4). In an ideal Rankine cycle, this compression is isentropic.

d. Constant Pressure Heat Addition (State 4 to 1): The high-pressure liquid water leaving the pump enters the boiler. Heat from an external source (e.g., fossil fuels, nuclear fission) is added to the water at constant pressure, turning it into high-pressure, high-temperature steam (state 1). This constant pressure process is where the heat energy is input into the cycle.

This is done with the help of water superheated as the moisture content gets near zero and is heat is produced by burning fossil fuels.

Liquid nitrogen can expand in a ratio of 1:694 and has a great energy density. When passed through a thin tube at a high flow rate the nitrogen expanded can give a thrust equivalent to a thermal cycle.

From analysis of [3] the efficient way of cooling nitrogen to its liquid state Is by using compressors.



The system is composed of two main cycles: the first, called the liquefaction cycle, creates cryogen by compressing and cooling it during off-peak hours to store energy in LN2. The stored energy is then extracted during peak hours by the expansion process during the recovery cycle, which liquefies and superheats the LN2 from the liquefaction cycle.

In order to extract the most energy possible from the cryogen, the recovery cycle combines open and closed Rankine cycles into one integrated cycle. The integration of the liquefaction and recovery cycles is made possible by storage systems, which store coldness from LN2 in the recovery mode and hot energy from compression in the liquefaction phase for later use in the recovery mode.

This separation of nitrogen can be reduced after a few power generation cycle since the Rankine cycle requires a constant pressure. The same gas can be cycled until or unless there is a leak in the system.

Existing steam powered powerplants can be easily converted to LN_2 power plants some means of thermal insulation and cryogenic cooling setups instead of boilers and condensers.

To achieve strong and steady flow compressing the fluid can be a vital method of achieving power generation.

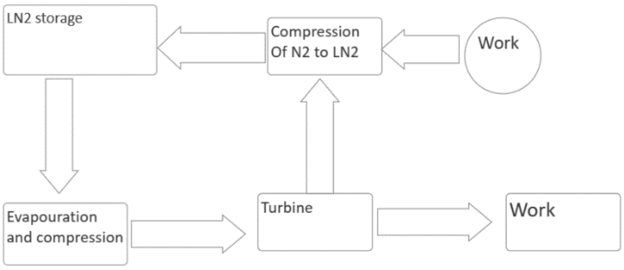
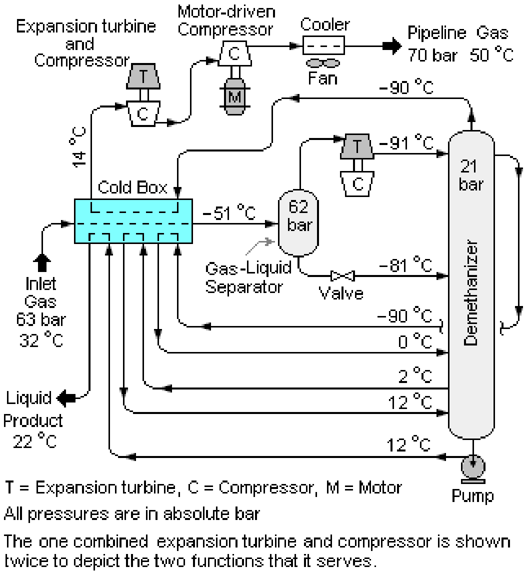


Figure 3: LN2 power plant cycle

V. TURBO EXPANDER

In order to achieve liquid nitrogen from gaseous nitrogen we use Turbo expander which is much more efficient and comparatively less power consuming to methods like Cryogenic Distillation and Joule–Thomson Effect.

(wikepedia)



T = Expansion turbine, C = Compressor, M = Motor
All pressures are in absolute bar
The one combined expansion turbine and compressor is shown twice to depict the two functions that it serves.

Figure 4: Turbo expander

Compressed and Cooled: First, the gaseous nitrogen undergoes compression, significantly raising its pressure and temperature. This hot, high-pressure gas then travels through a heat exchanger, where it gets pre-cooled by the exiting cold product (liquid nitrogen).

Expansion Does the Cooling: The pre-cooled nitrogen enters the turboexpander, a turbine with rotating blades. As the gas expands through these blades, it rapidly loses pressure and consequently cools down dramatically. This principle follows the Joule-Thomson effect, where a gas's temperature drops upon pressure reduction.

Double Duty: Power and Cooling: The expansion process within the turboexpander not only cools the nitrogen but also generates power due to the movement of the turbine blades. This recovered power can be used to help run the compressor, improving the overall efficiency of the liquefaction process.

Heat Exchange Optimization: The exiting cold gas from the turboexpander plays a key role. It passes through another heat exchanger, transferring its coldness back to the incoming high-pressure gas stream. This heat exchange significantly reduces the energy needed for pre-cooling, making the process more efficient.Improvements that can be made to improve performance of turbo expander

Multi-stage Expansion: Utilizing multiple turboexpanders in series achieves a more significant temperature drop in stages, leading to more efficient liquefaction.

Minimizing Energy Loss: Optimizing the design of the turboexpander to minimize friction and heat loss within the turbine improves its efficiency in extracting energy for the process.

Heat Exchanger Efficiency: Using highly efficient heat exchangers maximizes heat transfer between the cold and hot gas streams, reducing the overall energy required for liquefaction.

VI. EXPANSION CYCLE

Inject the liquid nitrogen into a high-pressure chamber through a nozzle. The sudden pressure drop causes rapid vaporization ("flash vaporization") due to the Joule-Thomson effect.

Figure 5:Piggyback system connection of storage tanks

Pre-heat the liquid nitrogen using a heat exchanger before it enters the turbine. This reduces the amount of energy needed for flash vaporization in the high-pressure chamber.

These methods have lots of limitations including the insulation leading to the compression and expansion chamber.

these methods require a significant amount of energy input, either for pressurization or pre-heating, which needs to be factored into the overall efficiency.

Compared to traditional working fluids like steam, liquid nitrogen has a lower energy density. This means you'd need a much larger volume of nitrogen to produce the same amount of power.

VII. STORAGE AND TRANSPORTATION

In a piggyback system for storing liquid nitrogen, multiple smaller, double-walled tanks are interconnected to create a modular storage solution. These tanks are typically cylindrical and constructed from stainless steel with a vacuum space between the inner and outer walls. This vacuum acts as excellent insulation, minimizing heat transfer and nitrogen evaporation.

Each tank has its own pressure relief valves and level sensors. The key to the piggyback system lies in the interconnecting piping. A series of valves and transfer lines allow for the controlled movement of liquid nitrogen between tanks.

This method ensures controlled pressure levels across the system and controlling the pressure before entering the turbine.

This method of storage allows for flexible storage capacity. Additional tanks can be easily added to the system if more storage is needed, or tanks can be taken offline for maintenance without impacting the entire system.

The ability to transfer liquid nitrogen between tanks allows for efficient inventory management and improved overall system efficiency.

VIII. ADAPTING EXISTING PLANTS

Adapting Existing Plants

Significant modifications would be required to adapt existing steam turbine power plants for any role involving liquid nitrogen. Here are some potential areas of focus:

Turbine Redesign: The existing turbine blades and materials might not be suitable for the extremely low temperatures of liquid nitrogen. Extensive redesign and potentially complete replacement of the turbine section might be necessary.

Heat Exchanger Integration: New heat exchangers would be needed to pre-heat compressed nitrogen (for a combined cycle) or pre-cool another working fluid like CO2.

IX. CONCLUSION

The modern world is inextricably linked to a reliable and readily available electricity supply. However, our dependence on conventional thermal power plants, which are major contributors to greenhouse gas emissions, presents a significant challenge. This method has its flaws and is an expensive process to make an initiative to it. If achieved with converting powerplants towards cryogenics it can drastically reducing carbon footprint. The path towards widespread adoption of cryogenic power generation necessitates further research and development efforts. Addressing technical challenges, optimizing system design, and ensuring cost-effectiveness are crucial steps in bringing this technology to fruition. However, the potential benefits of cryogenics – a cleaner environment, improved energy efficiency, and a more sustainable future – make it a promising avenue for long-term success.\

REFERENCES

[1] Wei, G., Kong, F., Shen, M., Tong, L., Jun, Y. B., Feng, W., Wang, L., & Ding, Y. (2023). A novel liquid natural gas combined cycle system integrated with liquid nitrogen energy storage and carbon capture for replacing coal-fired power plants: System modelling and 3E analysis. Energy Conversion and Management, 298, 117755. https://doi.org/10.1016/j.enconman.2023.117755
[2] RAVISHANKAR*,HOMESH KUMAR MAHATO*, Mr.S.BALAGURU** ICAMB 2009, Dec 14 – 16, 2009. Liquid Nitrogen Vehicle
[3] Khalil, K., Ahmad, A., Mahmoud, S., & Al-Dadah, R. (2017). Liquid air/nitrogen energy storage and power generation system for micro-grid applications. Journal of Cleaner Production, 164, 606–617. https://doi.org/10.1016/j.jclepro.2017.06.236
[4] Process Configuration of Liquid-nitrogen Energy Storage System (LESS) for maximum turnaround efficiency | Request PDF. (n.d.). ResearchGate. https://www.researchgate.net/publication/320642355_Process_Configuration_of_Liquid-nitrogen_Energy_Storage_System_LESS_for_Maximum_Turnaround_Efficiency
[5] Full report – BP Statistical Review of World Energy 2019. Available from: http://www.bp.com/.
[6] National Energy Technology Laboratory. "Rankine Cycle." https://netl.doe.gov/energy-analysis/details
[7] Moran, Michael J., et al. "Fundamentals of Engineering Thermodynamics." John Wiley & Sons, 2011. (Chapter 8: Power Cycles)