Cryogenics (Helium Liquefaction)

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Abstract- *This paper represents process for liquefaction of helium. Helium becomes liquid at cryogenic temperature so this paper includes the study of cryogenics. Liquefaction of gases is physical conversion of a gas into a liquid state (condensation). We all are familiar with the different phases of matter viz. gas, liquid and solid. The basic difference between these phases is the strength of intermolecular attraction between their molecules. By changing the strength of intermolecular attraction between molecules of any phase we can transform it to another phase. By reducing volume of gases we can change their phase. Most of the gases becomes liquid below -150 ℃ e.g. Helium, nitrogen, oxygen etc. In physics production or working with these super cold temperatures (below -150 ℃) is known as 'Cryogenics'. Liquefaction is used for analyzing the fundamental properties of gas molecules (intermolecular forces), for storage of gases, heat treatment, superconductivity, used as cryogenic fuel, food industry and used in medical science. The conclusion tells us about the liquefaction of gases and their advantages in today's world.*

Keywords- Helium liquefier, Heat exchangers, Turbine, Vacuum pumps, JT expansion.

1. INTRODUCTION

Cryogenics is the science and technology associated with generation of low temperature below 123 K or -150 degree Celsius. Cryogenics come from the two words Kryo means" very cold (frost)" and Genics means "To produce". So its "Science and art of producing very cold". Difference between cryogenics and refrigeration fluids are shown in table-1. Cryogenic liquids are used for accessing low temperatures. They are extremely cold, with boiling points below 123K. Carbon dioxide and nitrous oxide, which have slightly higher boiling points, are sometimes included in this category.

Table No.1:

Cryogen fluids and refrigeration fluids boiling temperature	
Cryogenics	**Refrigeration**
O_2 (90.19 K)	R134a (246.8 K)
Air(78.6 K)	R12 (243.3 K)
N_2 (77.36 K)	R22 (233 K)
H_2 (20.39 K)	Propane (231.1 K)
He (4.2 K)	Ethane (184 K)

The liquefaction of gases was first carried out by the English scientist Michael Faraday (1791-1867) in the early 1820s. There are three methods to liquefy gases. These are given below:-

A) By compressing the gas at temperatures less than its critical temperature.

B) By making the gas do some kind of work against an external force, causing the gas to lose energy and change to the liquid state.

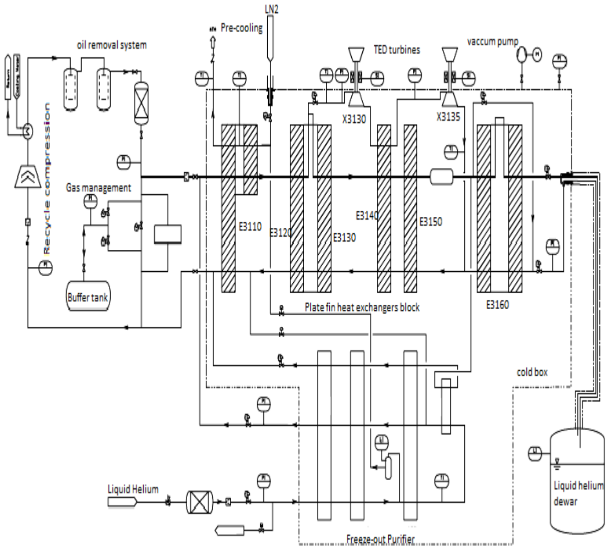
C) By making gas do work against its own internal forces, also causing it to lose energy and liquefy.

Many gases can be put into a liquid state at normal an atmospheric temperature by simple cooling; a few, such as CO_2, require pressurization as well. There are two most important factors needs to be achieved for liquefaction critical temperature and pressure. The critical temperature of a substance is the temperature at and above which vapour of the substance cannot be liquefied, no matter how much pressure is applied .Every substance has a critical temperature. The critical pressure of a substance is the pressure required to liquefy a gas at its critical temperature.

1.1 Helium liquefaction process

Helium liquefies at 4.4 k (-268.75 °c). Most of the helium liquefiers are Claude cycle based. Linde is the popular in industry for providing helium liquefaction solutions. Linde helium liquefiers are based on Claude cycle. Picture 3 shows the Linde helium liquefier piping & instrumentation diagram. Helium liquefaction process is explained below-

Low pressure (LP) helium gas, supplied to compressor. After compression of helium, helium enters the oil removal system where oil and moisture is trapped. Helium enters the cold box. It is cooled down in heat exchanger E3110 and E3120 by low pressure (LP) helium gas in counter flow. At its cold end liquid nitrogen (LN2)-evaporator is integrated so that pre-cooling of the HP-stream with LN2 becomes possible and the refrigeration or liquefaction capacity of the plant gets larger. The heat exchanger E3120 has two sections. Between these two sections the high pressure stream is split in two parts. The larger fraction gets expanded in turbine X3130. After a further cool-down in heat exchanger E3140 it enters turbine X3150. After exit from turbine X3150 helium circulates and cools down the heat exchangers.



Picture 1: (Helium liquefier PI & D)

After some circulations of helium, impure helium is fed to the integrated purifier unit. By cooling down the impure gas in counter current with cold HP gas impurities, nitrogen and traces of other gases condensate and/or freeze out. The purified gas is fed into the cold box HP-inlet side. By warming up the purifier will be regenerated, whereby the removed undesirable gases are discharged. When temperature of helium goes to 8-10 k the JT (Joule-Thomson) valve opens. By passing through helium liquefies and store in mother Dewar.

Picture 2.1 :(Helium liquefier)

Picture 2.2: (Mother Helium Dewar)

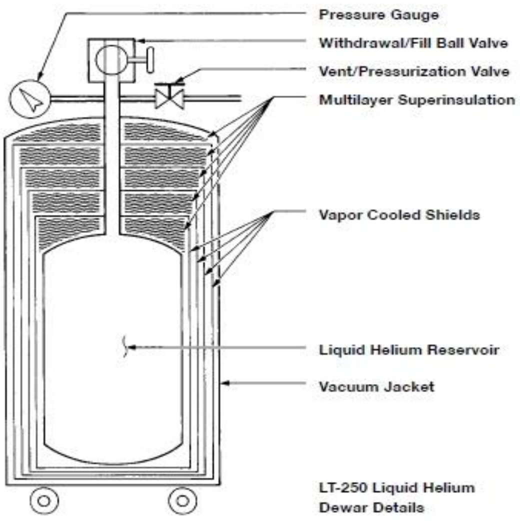
1.2 Storage and handling of cryogens (liquefied gases)

Cryogens have high expansion ratios, which average ~700:1. When they are heated (i.e. exposed to room temperature), they vaporize (turn into a gas) very rapidly. If the volume cannot be expanded (no outlet), the pressure will increase approximately 700-fold or until it blows something out. The typical container used to store and handle cryogenic fluids is the Dewar.

1.2.1 Dewar:

The Dewar is multi-walled designed with a vacuum jacket for insulation and pressure relief valves to protect against over-pressurization. Cryogens normally are stored at low pressure. These dewars are designed to insulate the heat. As we Know heat transfer in three ways i.e. Conduction, Convection and Radiation.

Conduction and convection is stopped by using vacuum as insulator and radiation is stopped by using MLI (multi layer insulator) as shown in picture.



Picture 3.1: (Liquid helium Dewar schematic)

Picure-3.2: (Liquid Helium Dewar)

1.3 Applications

Following are some areas showing applications of cryogenics-

-Liquid hydrogen is most widely used as fuel for rockets.

-Liquid oxygen is used as an oxidizer.

-Cryogens are used in medical industries.

-Cryogens are used in steel treatment as well as other industrial work.

-Cryogens are used to achieve very low temperature.

-Superconductivity of materials can be achieved by cryogens.

1.4 Advantages

Following are some advantages of cryogenics-

-It helps to Increases tensile strength, toughness and stability by using cryogenics treatment.

-It helps to achieve very low temperature.

-It is a pure fuel used in rockets.

-Most of gases are easily available in air for liquefaction.

-Cheaper fuel than other fuel used in rockets.

-It is the only way to super conduct materials.

1.5 Disadvantages

Following are some disadvantages of cryogenics-

-Handling & storing of cryogens is difficult.

-If cryogens is not handled properly it causes explosion.

-The process of liquefaction is expensive & complicated.

2. LITERATURE REVIEW

Devender Kumar et al.[1] concludes that cryogenics systems are which are capable of producing temperature below -150 .Linde cryogenics cycle is carefully observe and various gases are liquefy by it. A comprehensive energy analysis and other analysis of linde system are carried out by using various different gases with variable properties. Numerical computation is carried out to find out mutually dependency and effect of various properties on other properties and their involvement in energy destruction. It was observed that inlet properties and every part performance put huge impact on overall out of system Inlet pressure ranging from 3 to 6 bars and inlet Temperature at 298 K while compressor pressure ranging from 300 to 400 bars is optimum values of performance parameters for linde system.

Devender Kumar et al.[2] concludes that the study deal with energy comparative analysis of two cryogenics systems (i.e. Linde Hampson and Claude) in terms of second law efficiency and the output (which in form of liquefaction mass) of gases, The numerical computation was carried out for above systems and it was conclude that by joining extra accessories in system make a system efficient in output result but in other hand making system large , its cost and as well as useful energy destruction of overall system are degraded which seen in from of low second law efficiency. Two system giving same atmospherics input condition and varying compressor

pressure considered. Final results show the output of Claude system is more than the Linde system while second efficiency of Linde system is 18 % more than the Claude system at 300 bar compressor pressure for all gases.
Devender Kumar et al.[3] concludes that high cost of helium cryogenic system and less availability of work of high cost component turned the cryogenic science toward optimization. Second law efficiency analysis arises as a power tool for thermodynamic of these system components and selects the component on demand base parameters which reduces cost of whole system. Helium liquefaction system based on modified Claude system which well known as Collin system. A mathematical computational program is made on the basis of Collin system and with help of program whole system second law analysis on different input parameters is studied. Second law efficiency of system is 17.29 % and COP is 0.8687 when input at ambient condition and compressor pressure is 15 bar, but both start decreasing with further increases of compressor pressure whereas liquefaction mass ratio and Total work done is increases with increase in compressor pressure. Increase in Intermediate mass ratio of expander decrease the COP ,increase the second law efficiency, total work done and liquefaction mass of helium.

Sim´on Reif-Acherman [4] concludes that liquefaction of helium and the discovery of superconductivity are two of the most striking developments in low temperature physics. The fact that both were carried out in the laboratories of Kamerlingh Onnes at Leiden is not mere coincidence; the first one was indispensable for the researches that led to the second one. On the same way, liquefaction of helium was the consequence of several decades of efforts addressed to the process for liquefy the so-called then ‘permanent gases’. A whole study of this remarked subject must then include developments that extended, in his decisive step, more than a half of a century and that connect researches of many scientists throughout several European countries.

R.G. Sharma [5] concludes that the study of matter at very low temperature is fascinating because the phonon activity dies down at very low temperatures and one can look into the electronic behaviour minutely. Cryogenic baths of liquefied gases provide excellent medium to cool down samples. Liquefaction of a gas is a combination of an isothermal compression followed by an adiabatic expansion. Cascade process was adopted in liquefying oxygen by Cailletet and Pictet independently in 1877. The final cooling stage has always been a Joule-Thomsen (J-T) valve. Another important breakthrough came in 1898 when James Dewar succeeded in liquefying hydrogen making a temperature range of 20–14 K accessible. The moment of triumph came in July, 1908 when years of hard work by Kamerlingh Onnes at Leiden ultimately resulted in the liquefaction of helium. A temperature range of 4.2–0.8 K thus became accessible in the laboratory. A cascade process using Lair, LO2, LN2 and LH2 and the J-T expansion valve was employed. Within 3 years of this discovery came the defining moment of the discovery of superconductivity in April, 1911 in pure Hg at just below 4.2 K.

Algirdas Baskys et al.[6] concludes that as superconducting materials find their way into applications, there is increasing need to verify their performance at operating conditions. Testing of critical current with respect to temperature and magnetic field is of particular importance. However, testing facilities covering a range of temperatures and magnetic fields can be costly, especially when considering the cooling power required in the cryogenic system in the temperature range below 65 K (inaccessible for LN2). Critical currents in excess of 500 A are common for commercial samples, making the testing of such samples difficult in setups cooled via a cryocooler, moreover it often does not represent the actual cooling conditions that the sample will experience in service. This work reports the design and operation of a low-cost critical current testing facility, capable of testing samples in a temperature range of 10–65 K, with magnetic field up to 1.6 T and measuring critical currents up to 900 A with variable cooling power.

Andrew Townsend et al. [7] conclude that the testing of assemblies for use in cryogenic systems commonly includes evaluation at or near operating (therefore cryogenic) temperature. Typical assemblies include valves and pumps for use in liquid oxygen liquid hydrogen rocket engines. One frequently specified method of cryogenic external leakage testing requires the assembly, pressurized with gaseous helium (He), be immersed in a bath of liquid nitrogen (LN2) and allowed to thermally stabilize. Component interfaces are then visually inspected for leakage (bubbles). Unfortunately the liquid nitrogen will be boiling under normal, bench-top, test conditions. This boiling tends to mask even significant leakage. One little known and perhaps under-utilized property of helium is the seemingly counter-intuitive thermodynamic property that when ambient temperature helium is bubbled through boiling LN2 at a temperature of _195.8 _C, the temperature of the liquid nitrogen will reduce. This paper reports on the design and testing of a novel proof-of-concept helium injection control system confirming that it is possible to reduce the temperature of an LN2 bath below boiling point through the controlled injection of ambient temperature gaseous helium and then to efficiently maintain a reduced helium flow rate to maintain a stabilized liquid temperature, enabling clear visual observation of components immersed within the LN2. Helium saturation testing is performed and injection system sizing is discussed.

Dongli Liua et al. [8] concludes that for the numerical simulation of GM-type pulse tube cryocoolers (GMPTCs), several compressors with different input powers were characterized under static conditions, including their mass flow, input power, discharge and suction pressures. Based on the measured data, the relationships between suction volume flow, exergetic efficiency, and pressure ratio were found to be independent of the working gas amount contained in the compressor package. The empirically determined relations of suction volume flow and exergetic efficiency together with the volume distributions are given for the measured compressors. With these characteristics, the mass flow, electrical input power, discharge and suction pressures of the compressors operating in a GMPTC system can be predicted at various working conditions.

Q.-S Chen et al. [9] concludes that Liquefied natural gas (LNG) is being developed as a transportation fuel for heavy vehicles such as trucks and transit buses, to lessen the dependency on oil and to reduce greenhouse gas emissions. The LNG stations are properly designed to prevent the venting of natural gas (NG) from LNG tanks, which can cause evaporative greenhouse gas emissions and result in fluctuations of fuel flow and changes of fuel composition. Boil-off is caused by the heat added into the LNG fuel during the storage and fueling. Heat can leak into the LNG fuel through the shell of tank during the storage and through hoses and dispensers during the fueling. Gas from tanks onboard vehicles, when returned to LNG tanks, can add additional heat into the LNG fuel. A thermodynamic and heat transfer model has been developed to analyze different mechanisms of heat leak into the LNG fuel. The evolving of properties and compositions of LNG fuel inside LNG tanks is simulated. The effect of a number of buses fueled each day on the possible total fuel loss rate has been analyzed. It is found that by increasing the number of buses, fueled each day, the total fuel loss rate can be reduced significantly. It is proposed that an electric generator be used to consume the boil-off gas or a liquefier be used to re-liquefy the boil-off gas to reduce the tank pressure and eliminate fuel losses. These approaches can prevent boil-off of natural gas emissions, and reduce the costs of LNG as transportation fuel.

E. Shabagin et al. [10] concludes that To meet the increasing power demand in cities under the spatial constraints for cable channels, the application of high temperature superconducting (HTS) cables cooled with liquid nitrogen offers an increasingly attractive alternative to conventional cable solutions. This paper presents a differential equation model for three-phase concentric HTS cables, describing the temperature distribution in the various cable layers and in the liquid nitrogen flow. The design of the 1km long AmpaCity cable is used as a reference, which presently is the longest HTS cable installation in the world. The model considers the AC losses in the superconducting phases in addition to the external thermal load, as well as pressure losses in the coolant flow. The integrity of the algorithm is verified through energy conservation, yielding negligible numerical solver errors. The model is then applied to the operation of the AmpaCity cable. The final application study shows options for extending the cable length up to factor five, using a second cooling unit in combination with a mixed coolant.

Zhifeng Zhang et al. [11] conclude those recent years; voltage source converter-based multi-terminal high voltage DC power transmission (MTDC) is widely developed in the world. However, it is difficult for the existing DC breaker to cut off the fault transmission line with large short-circuit fault current. Then, it would be helpful to develop DC fault current limiter for the MTDC system. In this paper, DC superconducting fault current limiter (DCSFCL) is proposed to limit fault current. In order to study the resistance-time performance of the DCSFCL under the rapid change of fault current, a simulation model of Zhoushan MTDC system with DCSFCL is established, and the current-limiting performance of the DCSFCL at different location of the grid is studied. The simulations results show that DCSFCL can effectively limit short-circuit current and improve the operation reliability of MTDC system.

Ho-Myung Chang [12] concludes that a thermodynamic review is presented on cryogenic refrigeration cycles for the liquefaction process of natural gas. The main purpose of this review is to examine the thermodynamic structure of various cycles and provide a theoretical basis for selecting a cycle in accordance with different needs and design criteria. Based on existing or proposed liquefaction processes, sixteen ideal cycles are selected and the optimal conditions to achieve their best thermodynamic performance are investigated. The selected cycles include standard and modified versions of Joule–Thomson (JT) cycle, Brayton cycle, and their combined cycle with pure refrigerants (PR) or mixed refrigerants (MR). Full details of the cycles are presented and discussed in terms of FOM (figure of merit) and thermodynamic irreversibility. In addition, a new method of nomenclature is proposed to clearly identify the structure of cycles by abbreviation.

Woei-Shyan Lee et al. [13] concludes that the impact deformation behavior and associated micro structural evolutions of 7075-T6 aluminum alloy at cryogenic temperatures are investigated using a compressive split-Hopkinson pressure bar (SHPB) system. Cylindrical specimens are deformed at strain rates of 1 × 103 s−1, 2 × 103 s−1, 3 × 103 s−1 and 5 × 103 s−1 and temperatures of 0 °C, −100 °C and −196 °C. It is shown that the flow stress is strongly dependent on the strain rate and temperature. For a given temperature, the flow stress varies with the strain rate in accordance with a power law relation with an average exponent of 0.157 and activation energy of 0.7 kJ/mol. Moreover, the coupled effects of the strain rate and temperature on the flow stress are adequately described by the Zener-Hollomon parameter (Z). For all test temperatures, catastrophic failure occurs only under the highest strain rate of 5 × 103 s−1, and is the result of adiabatic shear. An increasing strain rate or reducing temperature leads to a greater dislocation density and a smaller grain size. Finally, the dependence of the flow stress on the micro structural properties of the impacted 7075-T6 specimens is well described by a specific Hall-Petch constitutive model with constants of K = 108.3 MPa µm1/2 and K′ = 16.1 MPa µm, respectively. Overall, the results presented in this study provide a useful insight into the combined effects of strain rate and temperature on the flow resistance and deformability of 7075-T6 alloy and confirm that 7075-T6 is well suited to the fabrication of fuel tanks and related structural components in the aerospace field.

Ziemowit M. Malecha et al. [14] concludes that an unexpected ejection of cryogen into large confined spaces can result in hazardous consequences. This paper presents the experimental results of the controlled release of liquid helium into the LHC tunnel at CERN. The experiment was designed to measure the oxygen concentration, temperature, and propagation of the helium-air mixture cloud in the LHC tunnel. This required the usage of novel, in-house manufactured, ultrasonic helium detectors. The experimental results showed an advantage of the ultrasonic sensors over traditional electrochemical sensors. Next, a minimal mathematical model was presented and implemented numerically. The experimental results contributed to the validation of the numerical model. A number of numerical calculations were performed in order to examine the consequences of a helium spill with different mass flows. This assisted in the evaluation of the critical helium mass flow, above which the oxygen concentration could drop below the safety limit. A satisfactory comparison of the experimental results and numerical calculations showed the accuracy of the assumptions of the proposed mathematical model.

Mitsuho Furuse et al. [15] conclude that this paper deals with the cooling system for high-T+c superconducting (HTS) generators for large capacity wind turbines. We have proposed a cooling system with a heat exchanger and circulation pumps to cool HTS field windings designed for 10 MW-class superconducting generators. In the cooling system, the refrigerants in the stationary and rotational systems are completely separated; heat between the two systems exchanges using a rotational-stationary heat exchanger. The refrigerant in rotational system is circulated by highly reliable pumps. We designed the rotational-stationary heat exchanger based on a conventional shell-and tube type heat exchanger. We also demonstrated that heat exchange in cryogenic temperature is possible with a commercially available heat exchanger. We devised a novel and highly reliable cryogenic helium circulation pump with magnetic reciprocating rotation system and verified its underlying principle with a small-scale model.

3. CONCLUSIONS

Liquefaction of gases like Helium is way more complex than normal refrigeration. It is not easy reach the cryogenic temperature but it can be achieved with above mentioned processes. Cryogenics is playing important role in various fields like medical, manufacturing, food industries and R&D. Applications like superconductivity, food preservation, cryotherapies, storage of gases and heat treatment of materials opens the gate of new possibilities. Transportation of cryogens is not easy also. Cryogens may have dangerous effects if not handled properly to overcome this specially designed vessels are being used. By using optimized heat exchangers, turbine and JT expansion liquefaction capacities have been increased by 50% to 100% in comparison to the old liquefier generation.

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