DESIGN AND DEVELOPMENT OF CRYOCOOLER BASED LIQUID NITROGEN PLANT

Thesis submitted in partial fulfilment of the requirements
For the degree of

Master of Technology (M. Tech) In

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Certificate of Approval

This is to certify that the thesis entitled "**DESIGN AND DEVELOPMENT OF CRYOCOOLER BASED LIQUID NITROGEN PLANT**", being submitted by **Mr. Ashish Kumar**, Roll No. 212ME5445 in the partial fulfillment of the requirements for the award of the Degree of Master of Technology in Mechanical Engineering ,is a research carried out by him at the department of mechanical engineering**,** National Institute of Technology Rourkela and Inter University Accelerator Center, New Delhi under our guidance and supervision.

The result presented in this thesis has not been, to the best of my knowledge, submitted to any other university or institute for the award of any degree.

The thesis in our opinion has reached the standards fulfilling the requirement for the award of the degree of in accordance with regulations of the institute

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CONTENTS

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ABSTRACT

Nowadays cryocoolers performance and reliability are continually improving. Consequently, they are more and more frequently used by physicists in their laboratory experiments or for commercial and space applications.

The advantage of cryocooler is the small size of its cold head due to this it can be mounted on top of a Dewar, thus reducing overall size of the liquefier setup making it possible to use it in demanding sites and laboratories where the consumption of liquid nitrogen is not in higher quantities. So the dewar which is mostly used to store liquid cryogen, here is used for production and storage purposes.

A cryocooler based Nitrogen liquefaction system was designed and developed which can be an ideal solution to the liquid nitrogen usage in laboratories. This setup uses a Cryomech Single stage Gifford-Mcmahon cryocooler to provide cooling and condensation of nitrogen at 80 K with the refrigeration capacity of 266 W (Rated) at 80K and a dewar specially fabricated with wider neck than usual dewar to accommodate cold head. The Gifford-Mcmahon cryocooler consist of compressor package, Helium Flex lines and cold head which is the heart and soul of this setup. The cold head is mounted into the top of the dewar and it extends down into the neck of the dewar for the purpose of cooling the nitrogen entering the dewar to 80K (-193ºC) at 0.5 bar gauge pressure which is the operating pressure for this dewar. The nitrogen gas liquefies on contact with the cold head heat exchanger. The liquefied nitrogen drips off the heat exchanger down into the dewar. This process would typically lower the pressure inside the dewar, but the regulator allows more nitrogen gas to enter the dewar to maintain the pressure at the preset level. The flow rate of the nitrogen gas into the dewar is controlled by the rate of liquefaction inside the dewar.

In the experimental dewar maximum liquefaction rate of 74 Ltr/day and in the main dewar liquefaction rate of 64 Ltr/day were achieved. The difference in liquefaction rate was due to the high radiation load coming on cryogen reservoir of main dewar.

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

Liquid nitrogen is obtained by cooling nitrogen gas to 77 K or -196 C at atmospheric conditions. At first nitrogen gas has to be separated from air for that membrane units are available or we can get liquid nitrogen directly from fractional distillation of liquid air. For large scale industrial use nitrogen is produced at air separation plant by liquefying air and separating liquid nitrogen by fractional distillation. Since 78% of air is made up of nitrogen and latent heat of evaporation of liquid nitrogen is 200 J/g it makes an ideal coolant for cryogenic applications like cooling thermal shields to reduce heat load coming on liquid helium, High Temperature Superconductors, superconducting magnets etc. The other uses of liquid nitrogen are metal treating, biological preservation, food preservation, cryotherapy, cryosurgery, cryonic preservation, sample treating at colder temperature etc.

Many laboratories around the world require liquid nitrogen for experimentation purpose but at the present time liquid nitrogen producing systems are larger and costlier than most laboratories can operate. Laboratories where the consumption of liquid nitrogen on daily bases is no more than 100 Ltr/day the option of buying liquid nitrogen from market is the ideal one but many suppliers supply liquid nitrogen in thousands of litres from tankers, hence means for storing liquid nitrogen in cryogenic storage tanks and providing pipelines if possible is an costlier affair.

1.1 BASIC PRINCIPLE USED

To produce liquid nitrogen basically we have to separate nitrogen from air and cool it down to 77 K to condense it. Condensation of liquid nitrogen is one thing and the other most important part is storage of liquid nitrogen; since it remains liquid at 77 K exposure to atmospheric conditions would not let it to remain in liquid state for long. Cryogenic storage tanks and Dewars are designed and manufactured to store nitrogen in its liquid form. These vessels are vacuum jacketed (double walled) to separate the vessel carrying liquid nitrogen from atmospheric conditions. The space between them is evacuated to reduce convection load in milli Watts and multi-layer insulation is used to reduce radiation heat load coming from vacuum jacket (at 300K) to cryogen reservoir (at 80 K) which is around 45 W/m^2.

In this project we have used a commercially available Cryomech Gifford-Mcmahon cryocooler to liquefy nitrogen gas at 80 K temperature. The rated refrigeration capacity by the company at 80 K is 266 W. The Gifford-Mcmahon cryocooler consist of compressor package, Helium Flex lines and cold head. The cold head is mounted into the top of the dewar and it extends down into the neck of the dewar for the purpose of cooling the nitrogen entering the dewar to 80K (-193ºC) at 0.5 bar gauge pressure which is the operating pressure for this dewar. The nitrogen gas liquefies on contact with the cold head heat exchanger. The liquefied nitrogen drips off the heat exchanger down into the dewar. This process would typically lower the pressure inside the dewar, but the regulator allows more nitrogen gas to enter the dewar to maintain the pressure at the preset level. The flow rate of the nitrogen gas into the dewar is controlled by the rate of liquefaction inside the dewar. So with the available refrigeration capacity at cold head we have obtained maximum production rate of 74 Litre/day in an experimental with 28 Litres capacity which was fabricated using the materials available at the IUAC. It has a wider neck to accommodate the cold head of cryocooler. Usually dewars have a smaller neck to reduce conduction load to the cryogen reservoir.

1.2 OBJECTIVE OF THE STUDY

1. To fabricate an experimental and main dewar for cryocooler to be assembled with it.
2. To get the required production rate of >60 Ltr/day.
3. Gather the required data from temperature sensors for theoretical and analytical study of the setup.
4. Optimize the production rate of the setup via condenser and gas precooling.
5. CFD modelling of different cases for better understanding of system.

1.3 COMPONENTS OF CRYOCOOLER BASED LIQUEFIER SETUP

The main component of the this setup are;

1. Compressor
2. Cold Head
3. Helium Flex Lines
4. Dewar
5. Pressure Regulator
6. Mass flow meter
7. Level Sensor

CHAPTER 2

LITERATURE REVIEW

Cryogenics is a branch of physics which deals with production of very low temperature and study their effect on matter; it is also defined as study of production of very low temperatures below 123 K. The limit 123 K includes the normal boiling point of atmospheric gasses, natural gas and methane. The condensation and distillation of air components remains the main driving force of cryogenic industry. Liquid hydrogen and oxygen is used as a fuel for rocket engines (cryogenic engine) and fuel cells for vehicles as an alternate to fossil fuels for clean energy. Large quantities of liquid nitrogen and oxygen are used in metallurgy industries.

2.1 HISTORY OF LIQUID AIR PRODUCTION

In the year 1872 Carl Von Linde liquefied air using Joule-Thomson principle. In the year 1877 Louis Paul Cailletet, a French mining engineer produced a fog of liquid oxygen by precooling and compressing it to 300 atm and allowing to expand suddenly at 1 atm. In the same year Raoul Pictet, Swiss physicist using a cascade system produced liquid oxygen. In 1883 Szygmunt Von Wroblewski and K. Olszewski first liquefied liquid nitrogen and oxygen at a laboratory in Cracow University. They were successful in condensing the gasses but were not able to keep them in liquid form because of the heat load coming from the ambient conditions. This problem was solved in 1892 by James Dewar, chemistry professor at Royal Institution of London. He developed the vacuum jacketed vessel for storing the liquid cryogen. Then in the year 1895 Carl Von Linde who had established Linde Eismaschinen AG in 1879 was granted patent industrial application of gas liquefaction in Germany. Now the Linde Company is one of the leaders in cryogenic engineering [1].

In the year 1959 a new refrigeration system was introduced by McMahon and W.E.Gifford for making small cryogenic refrigerators. The thermodynamic cycle came to be named as Gifford-McMahon cycle. The reason for the use of this cycle is its practicality, reliability and ease of construction. The device refrigerator which runs on this cycle is known as Gifford-McMahon cryocooler. Lately this refrigerating system is used for small scale liquefaction systems for Helium and Nitrogen, cooling of radiation shield for MRI and superconducting magnet systems etc. It is a smaller and efficient way to handle the heat load coming to liquid helium from atmospheric conditions

2.2 IDEA BEHIND CRYOCOOLER BASED LIQUID NITROGEN PLANT

At present small users (100 Ltr/day) prefers cryocooler based Nitrogen plant, medium users (200 to 1000 Ltr/day) prefer either Sterling or Linde plant. In small laboratory like material science, biomedical etc. where the quantities of liquid nitrogen required is less than 100 Ltr/day, if liquid nitrogen is available nearby and could be bought at these quantities it is the best option but if not cryocooler based liquefier are the best option in terms of price, reliability, space required, ease of maintenance etc.

A patent was filed by Chao Wang of Cryomech Inc. on Gas Liquefier on Oct 10, 2007 and was granted on Aug, 2009 using a pulse tube refrigerator with its cold head placed inside the neck of dewar or cryostat to liquefy gasses coming into the dewar[12]. The gas gets condensed on the condenser part of cold head and drips into the dewar. This was invented for the purpose of providing laboratories with liquid helium because most of helium liquefiers are larger in size and not for small laboratories purposes.

In this project we have used the principle applied by Chao Wang for helium liquefier to design and develop a Gifford-McMahon cryocooler based liquefier to produce liquid nitrogen more than 60 Ltr/day. We have also tried to study and apply the precooling effect given by regenerator part of cold head to enhance the production rate of the setup and to reduce the boil-off rate of liquid nitrogen from the heat load coming into dewar. The precooling effect is notably visible in pulse tube liquefiers which was observed and explained by E.D. Marquardt, Ray Radebaugh, and A.P. Peskin in the paper 'Vapor Precooling in a Pulse Tube Liquefier' presented at Presented at the 11th International Cryocooler Conference.

CHAPTER 3

DESCRIPTION OF PRINCIPLE COMPONENTS OF LIQUEFIER

3.1 GIFFORD-MCMAHON CRYOCOOLER

3.1.1 INTRODUCTION

In the year 1959 W.E Gifford introduced a new thermodynamic cycle which could be used to make cryogenic refrigerators. This cycle came to be known as Gifford-Mcmahon cycle. In the year 1960 first Gifford-Mcmahon cryocoolers were developed based on closed loop helium refrigeration cycles. In 1980s Gifford-Mcmahon cryocoolers were used for cooling charcoal adsorbers in cryopumps. In the late 1980s these cryocoolers were used in MRI for cooling radiation shield and hence reducing the evaporation rate of liquid helium used for maintaining the temperature of superconducting magnets. Then with the use of high heat capacity materials in regenerator in the range 4K and above allowed the GM cryocooler to achieve temperature of 4.2K.

Nowadays due to precooling of reservoirs with evaporating helium gas conduction load from atmosphere can be reduced upto 10 times, and the radiation load can be handled quite well by GM cryocoolers which have approx. 1.5 W of refrigeration capacity at 4.2 K. This ability of GM cryocooler is used in Cryo-free systems and compact MRI systems. These are small in size, can be operated in any orientation, reliable, easy to construct and have low cost of maintenance. GM cryocoolers are used where use of liquid nitrogen and liquid helium handling is difficult or unavailable.

In this project we have used a Cryomech single stage cryocooler with a refrigerating capacity of 266W at 80K and can go upto 25K at no load condition. The reason to choose this cryocooler was its cost and the cooling capacity at 80K. Requirement of this project was the production rate of more than 60 Ltr/day hence a higher refrigeration capacity cryocooler was chosen. Cost of the pulse tube cryocooler is higher than GM cryocooler and it consume almost double the power GM cryocooler.

3.1.2 COMPONENTS OF GIFFORD-MCMAHON CRYOCOOLER

There are three major components in Gifford-Mcmahon cryocooler,

1) Compressor Package: - Primarily it compresses the refrigerant and removes heat from heat from the system. In the compressor package oil lubricated compressor compresses 99.999% pure helium returning from a low pressure line from cold head. It compresses Helium upto working pressure of approx. 235 psi and the heat generated from this process is removed via a heat exchanger, which is cooled by a cold water supply provided to the compressor package. The oil from the compression process is removed by a series of oil separators and filters. The compressed helium then goes to the cold head via high pressure flex lines.

2) Cold Head: - It is connected with compressor package with helium flex lines for helium gas transfer and an electric power cable for the motor in the cold head. The compressor provides necessary Helium gas flow rate at the high and low pressure of the expander to provide necessary refrigeration capacity. In the cold head Helium gas expands adiabatically after passing through a regenerator housed inside a pneumatic expander which cools down the helium gas further to provide necessary refrigeration capacity. The displacer is housed inside a low thermal conductivity material. The whole movement of displacer is controlled by a rotary valve which is driven by the electric motor.

3) Cold Head Heat Exchanger: - It is a Nickel plated Cu heat exchanger vacuum brazed at the bottom of the cold head. This is the part where heat is transferred from system to the cold Helium gas inside the cold head.

4) Flex Lines: - Helium flex lines are corrugated stainless steel hoses to transfer helium from compressor package to cold head and back. It is a leak proof detachable line.

3.1.3 WORKING OF GM CRYOCOOLER

A Gifford-Mcmahon cycle can be described in 4 steps which takes place periodically,

1) Here the displacer in the upward position and the inlet valve to the helium compressor is opened. The helium gas passes through the low pressure flex line to the compressor

where it is compressed to around 235 psi. Then it goes through the heat exchanger to cool down to atmospheric conditions.

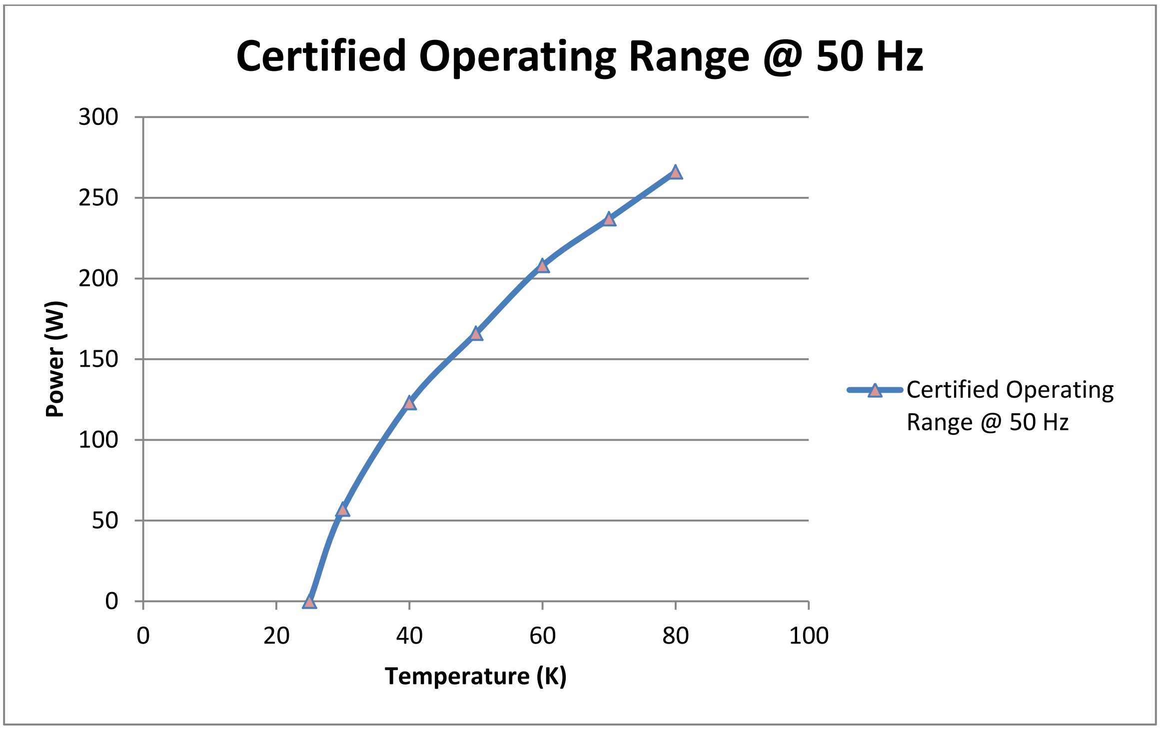
2) After passing through the compressor and the cooling down to atmospheric condition via heat exchanger in the compressor package it goes to the small volume above the displacer via high pressure flex line. Then the displacer is pushed downwards and the gas expands hence taking more gas from the compressor. This Helium gas passes through the regenerators giving its enthalpy to the regenerator material and cools down.
3) Now the inlet valve to high pressure flex line is closed and the exhaust valve to the low pressure line is opened. Then the helium gas cools down further by expanding in the space below displacer hence moving the displacer in the top position. This process provides the required cooling in single or two stage cryocoolers. Then the gas passes through the regenerators hence transferring its enthalpy to the regenerator material.
4) The gas had passed through the regenerator cooling it and then pushed the displacer it warms up. Then it passes through low pressure flex line towards the helium compressor. This process continues periodically in a cycle to provide required refrigeration capacity.

The electric motor in the cold head actuates the high and low pressure valves for the control of the valves and the displacer driven pneumatically. There is a certain level of vibrations transferred to the body of cold head and hence to the experimental setup due to the movement of displacer and electric motor. These vibrations are quite tolerable for the maximum setups at cryogenic temperatures.

Fig. 3.1 Cold Head OF GM Cryocooler

Fig. 3.2 Cold Head with Compressor unit

Fig. 3.3 Capacity curve of AL300 (Courtesy of Cryomech Inc.) [20]



Specification of GM Cryocooler (courtesy of Cryomech Inc.) [20]

Cold head: AL300

Weight…………………………………………………………….41 lb. (18.6 kg)

Cooling Capacity…………………………………………………….266W @ 80K

Cool down time………………………………………………………... 15 minutes to 80K

Lowest temperature………………………………………………..... 25K with no load

Compressor Package: CP2800

Helium static pressure ……………….....................................15.9 ± .34 bar (230 ± 5 PSIG)

Weight……………………………………………………..119 kg

Electrical Rating…………………….................................... 200/230 or 440/480VAC, 3Ph, 60Hz // 200 or 380/415VAC, 3Ph, 50Hz

Power Consumption @ Steady State………………………..5.5//6 kW

3.2 LIQUID NITROGEN DEWAR

3.2.1 INTRODUCTION

Dewar is a cryogenic vessel used to store liquid cryogens like nitrogen, Helium, oxygen etc. Dewar's for liquid nitrogen usually consist of vessel surrounded by vacuum jacket which isolates vessel from atmospheric environment. Some dewars are constructed from epoxy-fiberglass and Aluminium but the most reliable are made from stainless steel primarily due to its ruggedness, and has a relatively low thermal conductivity. It also can be permanently joined to similar or dissimilar metals like Brass, Copper etc. by welding, brazing or silver soldering. Such joints can withstand many thermal cycles between room temperature and nitrogen temperature and remain leak tight throughout its life [14].

The Dewar used for this setup have an all welded construction with an access directly to the cryogen vessel through top of the dewar. It also have an evacuating valve for evacuating the space around the vessel carrying liquid cryogen which reduces the gas conduction heat load from a vessel carrying cryogen and vacuum jacket. If vacuum is not of the order of 10^{-5} mbar or above gas conduction will increase from vacuum jacket (at room temperature) to inner vessel (at 77K) due to higher number of gas molecules. Evidence of low quality vacuum we can see as moisture condensation outside vacuum jacket.

A pressure relief is provided to relieve the pressure builds up inside the vessel in case of vacuum and internal leak. Such type of leaks will result in cryogen coming in contact with warm air thus increasing the heat load onto the vessel hence increasing pressure in vessel carrying liquid cryogen. Relief valves are set to open at a particular pressure above atmospheric pressure, will safely vent cryogen to the outside of dewar. In this Dewar a 15 psi relief valve has been provided for safety purpose. The dewar was modelled using Solidworks software.

Another important part of liquid nitrogen dewar is multi-layer insulation surrounding the cryogen vessel for reducing the radiation heat load coming from vacuum jacket at room temperature

3.2.2 MAIN PARTS OF LN2 DEWAR

VACUUM JACKET

In Liquid nitrogen dewar the cryogen reservoir is surrounded by a jacket mainly made of stainless steel. The space between cryogen reservoir and vacuum jacket is evacuated through pull up valve to a low vacuum of the order of >10^{-5} mbar. Vacuum of the order of >10-5 mbar is necessary in liquid nitrogen dewar so that gas conduction load coming at cryogen reservoir which is at 80K can be reduced in mW range. A pumping station consisting of turbomolecular or Diffusion pump in series with a rotary pump is used to produce vacuum in 10^{-6} mbar range through the pull up valve and when vacuum is achieved valve can be closed.

CRYOGEN RESERVOIR

It is vessel normally made of stainless steel which is used to store liquid cryogen. It can be welded to the vacuum jacket via stainless steel neck or can be joined with G10 neck to reduce the conduction load coming from atmospheric conditions. The heat load coming to reservoir should be minimized to have low boil off rate of cryogen. Gas conduction load at cryogen reservoir is reduced when vacuum of the order of 10^{-5} or above is produced, which remains in few milli watts. The other heat load is radiation load which overtakes the convection load when vacuum is created between reservoir and jacket. In case of liquid nitrogen reservoir it is almost 45 W/m2 which is very high. So to reduce the radiation load we have to wrap highly reflective materials on the cryogen vessel, these materials are known as multi-layer insulation.

RELIEF VALVE

It is a valve which is used to limit the pressure build up inside a pressure vessel. It is designed to open at a preset value to protect the pressure vessel from being subjected to higher pressure than designed value. When pressure inside a vessel exceeds above set value, the relief valve opens and fluid flows through it until pressure inside vessel reduce to the reset point of the valve. Once it reaches there the valve will close. The process valve resetting to its original position is known as blowdown which is stated as percentage of set pressure, which refers to how much pressure needs to drop before the valve can reset. It can be adjusted in some valves and in some it comes as a preset value. In our dewar we have used a Swagelok 15 psi spring loaded relief valve.

MULTI-LAYER INSULATION OR SUPERINSULATION

Multi-Layer insulation is an insulation consisting of multiple layers of thin Aluminium sheets with high reflectivity intended to reduce the radiation heat load on the cryogen reservoir. The thickness of the Aluminium is in the range 5 to 10 nm on Mylar film. Usually a fibrous material of low emissivity and thermal conductivity is placed between the layers; it acts as a thermal insulator between the layers. Multi-layer insulation must work in vacuum so that conduction and convection load are much less and the radiation load dominates. The multiple sheets of Aluminium must not be compressed too tightly or the solid conduction dominates the reduction of radiative heat transfer. The other downside of compressing the layers too tight is the difficulty in producing high vacuum between them, hence the system vacuum deteriorates and the conduction and convection load increases.

Fig. 3.4 Experimental Dewar

Fig. 3.5 Main Dewar

3.3 VACUUM PUMP

3.3.1 Why Vacuum is required?

In liquid Nitrogen and Helium dewar we need to have least amount of heat load coming into the cryogen reservoir (at 77K or 4.2K). The maximum amount of heat load that can be transferred into the cryogen reservoir is due to natural convection from atmospheric condition (at 300K), hence to reduce this heat load we have to evacuate the space between vacuum jacket and cryogen reservoir. The space is evacuated using pumping station to create vacuum in the range of $>10^{-5}$ mbar. At low and high vacuum the heat transfer coefficient varies proportionally to pressure inside vacuum jacket, hence higher the quality of vacuum less is the gas conduction load coming into the cryogen reservoir.

The number of gas molecules reduces when vacuum is created, the mean free path of the molecules increases and at 10^{-4} mbar pressure it is approximately 100 cm. The mean free path of molecules begins to exceed the distance between the surfaces and heat is carried by the molecules from one surface to other without colliding with another molecule, this process is known as gas conduction. This heat load reduces to few milli watts in case of liquid nitrogen for vacuum of 10^{-5} mbar or above.

We have designed an experimental dewar with cryogen reservoir for liquid nitrogen and a vacuum jacket. The space between vacuum jacket and cryogen reservoir is evacuated with help of pumping station. The pumping station consists of turbomolecular pump backed by a rotary or scroll pumps. This arrangement of pumps is enough to produce high vacuum of above 10^{-5} mbar. The advantage of using turbomolecular pumping station against diffusion pumping station is that the turbomolecular and the rotary pump can be started simultaneously, while in the case of diffusion pump we have to wait for the pressure to reduce to 10^{-2} mbar to start the diffusion pump or else oxidation of oil will happen inside the diffusion pump, but turbomolecular pumps are costlier than diffusion pumps

3.3.2 ROTARY PUMP

This pump works on the principle of rotating vanes creating suction at the inlet and then exhausting gas at the outlet. Rotary pump are usually used as a backing pump for Diffusion or turbomolecular pump. These pumps can give vacuum of 10^{-2} mbar for single stage and 10^{-3} mbar for double stage pump. Such pressure are not enough for liquid nitrogen dewar which operate between 77K to 300K. In the case of liquid Helium these pressure works if the evacuation valve is sealed before pouring liquid helium inside the dewar because of the helium reservoir will cryopumps vacuum of the dewar to a pressure of 10^{-6} mbar or below.

Most of the laboratories use rotary pump as a backing pump for turbo or diffusion pump to produce high vacuum inside the dewar. In case of helium pumping for turbomolecular pumps a two stage rotary pump is required to maintain as low pressure as possible during venting.

3.3.3 TURBOMOLECULAR PUMPS

This pump works on the principle that directional motion can be given to the gas molecules by repeated collision with rapidly moving series of rotating blades. In the range of higher vacuum the numbers of molecules are very less and the mean free path between them is large thus the collision of molecules with each other is less frequent than with the walls of rotating blades, hence increasing the influence of rotating blades on the molecules. The operating range of these pumps is 10^{-2} mbar to 10^{-10} mbar pressure.

The turbomolecular pump is especially useful in production clean high vacuum since the compression ratio is dependent on mass of molecules. The heavier molecules like oil particles can be easily removed so that no backstreaming of oil particles occurs and we get a clean vacuum.

3.3.4 EVACUATION OF DEWAR:

Vacuum was created in Dewar using the turbomolecuar pumping station. The pumping station is made of Varian SD-301 rotary pump and Varian Turbomolecular pump. The rotary pump acts as a backup to turbo pump and both are connected in series.

We were able to achieve pressure of 3.5E-5 mbar and 1.9E-5 mbar while the cryocooler was producing liquid nitrogen. Vacuum receded to that value because moisture and other heavier molecules condensed on the surface of the cryogen reservoir, thus increasing the quality of vacuum.

3.4 INSTRUMENTATION

3.4.1 LEVEL SENSOR

Level sensor is used detect the level of substances that flows which includes slurries, granular flow, fluidized beds etc. The level sensing capabilities can be from point to point or continues for a section. Continues level sensor measure level within a specified range giving exact value of level at certain place, while point level sensor can give level above or below a certain sensing point. In cryogenic application capacitance based level sensor is most preferred for liquid nitrogen and oxygen while for liquid helium resistive type level sensor is used. For liquid helium superconducting wire like NbTi whose transition temperature is 9.2K can be used to measure level of liquid helium.

Capacitance Based level Sensor

For liquid nitrogen we have to use a capacitance based level sensor. The instrument sensing element has a 3/8th outer diameter cylindrical capacitor and an inner cylinder. The sensor allows the cryogenic liquid to become dielectric in the annular space. The instrument measures the sensor capacitance which is directly related to the percentage of the sensor immersed in the cryogenic liquid. The length of the sensor is 1m with the active length 33 cm i.e. the level of liquid can be measured till 33 cm of height inside the cryogenic reservoir.

3.4.2 VACUUM GAUGE

The quality of vacuum that exist in system can only be measured by a sole parameter pressure. So pressure measurement is an important process to measure vacuum accurately. Conventional measuring equipment like U- tube manometer, McLeod gauge are of no use in vacuum, since the pressure is below atmospheric pressure. So the gauges have to measure other pressure dependent properties which are secondary to pressure but are sensitive to change in pressure like thermal conductivity, ionization of gases etc. these gauges have to be calibrated with standard gauges.

WORKING PRINCIPLE

A Pirani gauge utilizes variation in thermal conductivity of gas inside the vacuum as criteria to measure pressure inside the system. The full range of Pirani gauges are atmospheric pressure to 10^{-3} mbar. While the cold cathode gauge measures concentration of ionized gas molecules between its two cathode plates and a hollow cylindrical anode. The density of ions produced between the plates is directly proportional to density of gas, hence proportional to pressure.

To measure vacuum we have used Pfeiffer Vacuum Compact full Range gauge PKR 251 capable of measuring pressure from 1013 mbar to 5E-9 mbar. This gauge consist two measuring system Pirani and cold cathode system both are combined to give a single measurement system. The analog signal coming out of this gauge is interpreted by Pfeiffer Vacuum Dual gauge to display the correct value of vacuum on its digital display.

3.4.3 MASS FLOW METER

It is a device used to measure mass flow rate of a particular gas. We have an Aalborg GFM-47 mass flow meter for liquid nitrogen. The working range of this device is 0-2 g/sec for liquid nitrogen and can be used for other gasses too, due its dependency on thermal conductivity and specific heat of that gas. The flow meter was calibrated with nitrogen gas for the particular range.

Working Principle

A stream of gas entering the mass flow meter is separated into two streams by shunting a small portion of the flow. One goes through the primary conduit and the other to the sensor tube to ensure laminar flow in both tubes. According to principles of fluid dynamics laminar flow rates of gas in two conduits are proportional to each other. Therefore flow rate measured in sensor tube is directly proportional to flow rate in transducer. To sense the flow in sensor tube, heat flux is induced at two sections of sensor tube by means of heater coils the heat is carried by the gas downstream and the temperature dependent resistance differential is detected by the electronic circuit. The measured gradient at sensor winding is linearly proportional to instantaneous flow rate.

3.4.4 TEMPERATURE MONITOR

It is an instrument used measure, interpret and display accurate temperature data from different types of temperature sensors. We have used a Lakeshore 218 temperature monitor to measure the data coming out of our eight silicone diode temperature sensors. It is an eight channel input temperature monitor that can be used for resistive or diode types of temperature sensor. The input measurement was specifically designed for cryogenic temperature. It has an automated data collection for the data coming in its eight channels for specific period of time Less number of sensors more data can be saved in temperature monitor due to low memory space for storage of data. It also includes computer interface like IEEE-488 and serial port to integrate it with computers to collect and monitor data.

3.4.5 TEMPERATURE SENSOR

Silicone diode sensors are the sensor of choice for zero magnetic field temperature measurement in the range of 4K to 300K. The forward voltage of sensor at constant current with respect change in temperature is a well-defined aspect in cryogenics. These are the most widely used sensors because of theirs stability, reproducibility and interchangeability. The small size of sensor is another useful feature when space constraints are present. They are extremely helpful when rapid temperature response is required for small thermal mass. Forward voltage of approximately 1 V is generated with constant excitation current of 10 µA. Sensor has good sensitivity because of higher voltages are involved and it increases rapidly below 25K.

Disadvantages of silicon sensors are that they do not provide absolute accuracy, and the reproducibility of these thermometers on thermal cycling is not quite as good as the other semiconductor-like thermometers.

CALIBRATION

In silicon diode sensors forward voltage reading is current dependent, which requires calibration and operation to be at constant current. Usually 10 µA current is used for calibrating Silicon diodes temperature sensor.

We have a two stage cryocooler based setup in IUAC basically used for magnetic susceptibility measurements, observing superconductivity transition etc. The setup was used to calibrate temperature sensors. It has a probe to place samples on it and subject them to low temperatures. The setup has a capability to go upto 10 K temperature. The probe to around 10 K and then constantly heated up to 300 K using a temperature controller in steps of 5K to 10K while continually measuring voltage across the diode at that temperature to get a VT curve which can be feed into temperature monitor for that sensor. We have calibrated 8 diodes whose VT curve can be seen in Fig.3.6 and placed them at certain places on the experimental dewar and on the cold head of GM cryocooler using GE varnish and aluminium tape which can be seen in Fig.3.7 and 3.8.

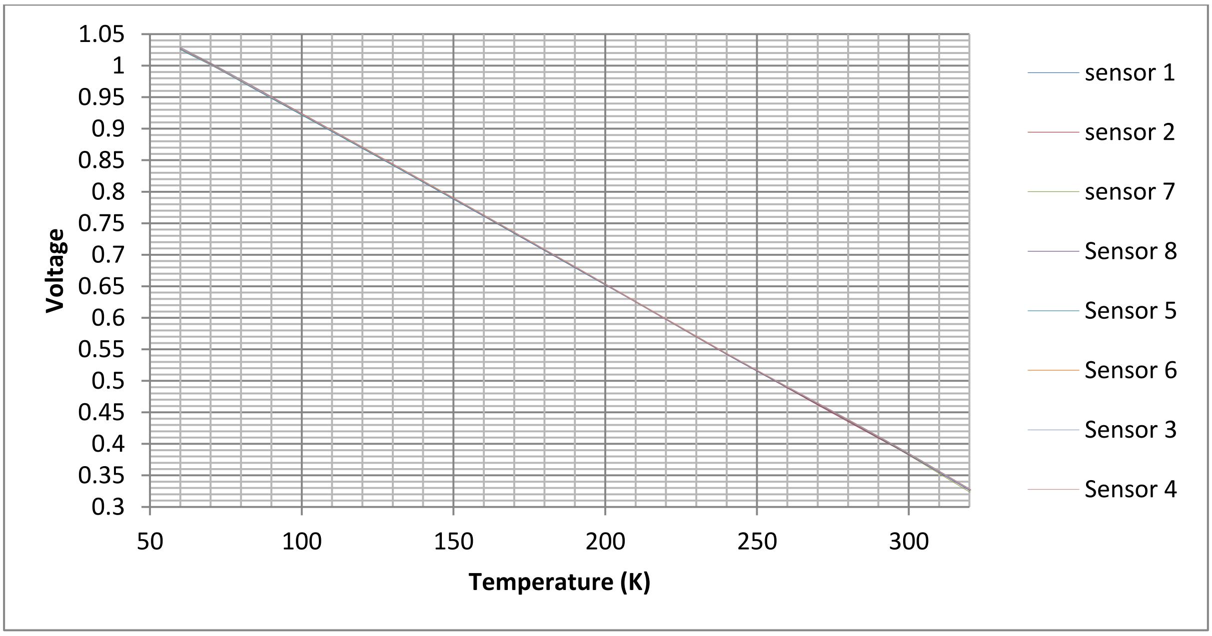


Fig. 3.6 Calibration Curve Temperature Sensors

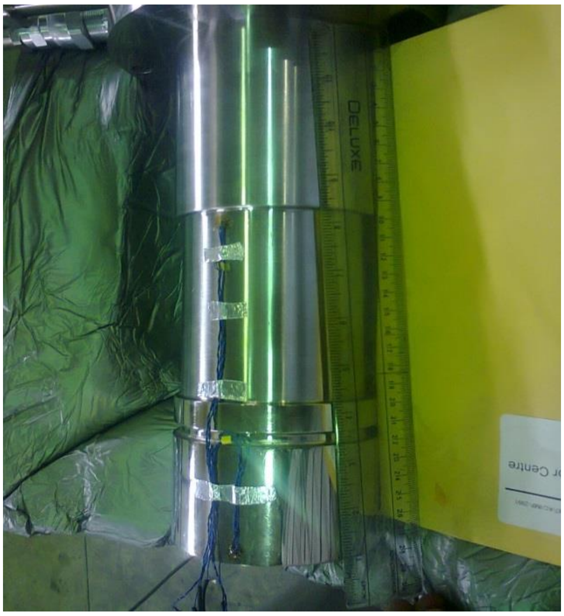


fig. 3.7 Sensors on the Cold Head of Cryocooler fig 3.8 Sensors on the neck of dewar

CHAPTER 4

THERMAL DESIGN OF EXPERIMENTAL DEWAR

4.1 INTRODUCTION

Thermal designing in cryogenic systems is the most important step in designing of a cryogenic apparatus; we can modify the setup after machining for success but heat transfer has to be minimal and in acceptable range for the apparatus to give the required performance from it. The heat transfer basically occurs in three ways;

- Conduction - heat transfer through solid
- Convection - heat transfer through liquids and gases
- Radiation – heat transfer through space

Heat transfer through conduction can be precisely calculated but in the case heat transfer through convection and radiation a reasonable estimate can be done.

4.2 HEAT LOAD COMING INTO DEWAR

4.2.1 CONDUCTION HEAT LOAD:

The conduction heat load that can be transferred to liquid nitrogen through the neck portion of the Dewar since it is the only support which is suspending the cryogen reservoir inside vacuum jacket. One dimensional heat transfer equation for conduction,

$$\dot{Q} = -kAdT/dx \qquad (1)$$

Here $\dot{Q} = \text{Heat transferred through the neck}$ $\quad A = \text{Cross} - \text{Sectional area of neck}$

Since the thermal conductivity of Stainless steel varies with temperature, we take the value of mean thermal conductivity from low temperature to higher temperature.

$$\bar{k} = \int_{T1}^{T2} KdT \qquad (2)$$

With the mean thermal conductivity considered the heat transfer equation becomes,

$$\dot{Q} = \bar{k}\frac{A}{L} \qquad (3)$$

CASE

We have a SS304 neck with ID= 108.2 mm and OD = 114.3 mm and length 320 mm. one end is at 300K and the other at 80K for the maximum possible heat load that can be transferred to the liquid nitrogen.

For SS304 mean thermal conductivity from 300 to 80 K = 2711W/m (from Experimental Temperature for Low-temperature measurements by Jack.W.Ekin)

Cross-sectional area of the pipe A = $1.066*10^{-3}$ m2

Therefore total heat transferred through the neck from (3), $\dot{Q} = \overline{\overline{K}} \times A/L$

$$\dot{Q} = 2711 \times 1.066 \times \frac{10^{-3}}{0.3}$$

$$\dot{Q} = 9.63 \text{ W}$$

REDUCTION OF CONDUCTION HEAT LOAD:

To reduce the conduction heat load with same length we made a groove of 75 mm length and 1.5 mm depth in the middle of the neck of Dewar, thus reducing the area for heat transfer.

Since it is not possible to calculate theoretically the amount of heat transfer due to many unknowns, we calculated the heat transferred through the neck using steady state thermal analysis from Ansys software. The total heat load was reduced to 7.06 W by making a groove on the neck. The temperature and Heat flux profiles can be seen in fig. 4.1 and 4.2.

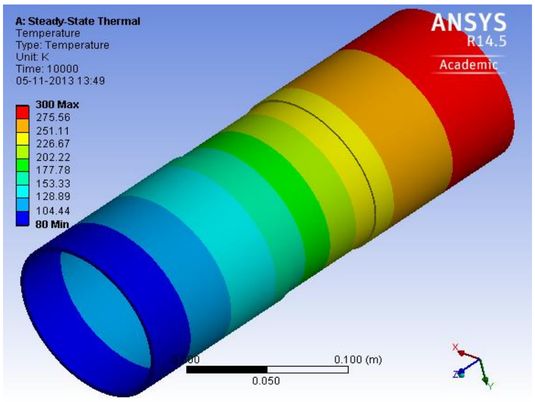


Fig 4.1 Temperature Profile of Neck

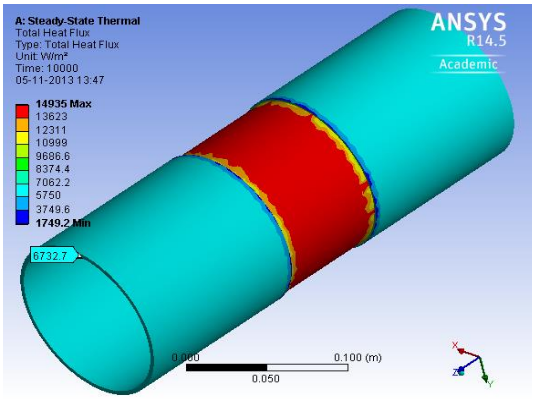


fig 4.2 Heat flux profile of neck

4.2.2 GAS CONDUCTION HEAT LOAD:

In case of heat transfer at atmospheric conditions molecules at higher energy has to travel short distances in the order of nm and strikes a lower energy molecules and transfers energy. on the other hand in free molecular conduction, the probability of gas molecules striking each other is very low, hence the molecule travels through the space from hot temperature to lower temperature surface and transfers energy directly to surface.

At pressures below about 10^{-2} mbar, the mean free path of the molecule begins to exceed the distance between surfaces and heat is carried by Molecular-Kinetic processes.

In the molecular kinetic regime, the heat exchange depends on

- Number of molecules striking the surface/unit time.
- The thermal equalization of the molecule with the surface.
- Probability that the molecule sticks to the surface.

In the free molecular regime, heat transfer between two parallel surfaces can be calculated using the expression,

$$\dot{Q} = F_a G P A_1 (T_2 - T_1) \qquad (1)$$

Where G is the property dependent function ,

$$G = [(\gamma + 1)/(\gamma - 1)] * (g_c R/8\Pi T)\hat{}\ 0.5 \qquad (2)$$

And Fa is the accommodation coefficient factor for concentric cylinder,

$$1/F_a = 1/a_1 + A_1/A_2[1/a_2 - 1] \qquad (3)$$

Where ‘a’ is the accommodation factor of air which is 0.85 at T_2= 300K and 1 at T_1= at 80K

A_1 = Area of Inner chamber

A_2 = Area of outer chamber

F_a = Average accommodation factor

R = Gas constant

P = Vacuum pressure

g_c = gravitational constant

CASE

In our case we have dewar with the area of vacuum jacket A_2 = 2.5256 m^2 at temperature T_2= 300K and the area of cryogen reservoir A_1 = 0.5356 m^2 at temperature T_1= 80K substituting the above values and taking accommodation factor of air is 0.85 at vacuum jacket and 1 at cryogen reservoir. We can calculate Fa and then G. The final result comes out to be

Let us calculate the accommodation coefficient factor for our setup using equation (3)

$$1/F_a = 1/a_1 + A_1/A_2[1/a_2 - 1]$$

Substituting the values in above equation we get,

$$1/F_a = 1/1 + (0.5356/2.5256)[1/0.85-1]$$

$$Fa = 0.964$$

Now to calculate the property dependent function G using equation (2), substituting the value of required constants in equation below we get,

$$G = [(\gamma + 1)/(\gamma - 1)] * (g_c R/8\Pi T)\char`^ 0.5$$

$$G = \left[\left(\frac{2.4}{0.4}\right)\right] * [\frac{1*287}{8\Pi*300}]\char`^0.5$$

$$G = 1.1706\ m/(s - K)$$

Substituting the value of Fa and G in the equation (1) to get the heat transferred by gas conduction between vacuum jacket and the cryogen reservoir in terms of pressure where P is in Pascal

$$\dot{Q} = F_a G P A_1 (T_2 - T_1)$$

$$\dot{Q} = 0.964 * 1.1706 * 0.5356 * (300 - 80) * P$$

$$\dot{Q} = 132.9 * P$$

Therefore the heat transferred through gas conduction is 0.132 W at 10^{-3} Pa or 10^{-5} mbar

4.2.3 HEAT LOAD RADIATION**:**

All bodies emit energy constantly by a process electromagnetic radiation. The intensity of energy flux depends on the temperature of the body and its surface. In the case of conduction and convection a medium is required to transfer energy but no intervening medium is necessary to transfer radiative energy.

The relation of radiation heat transfer between two grey bodies is,

$$\dot{Q} = \frac{\sigma(T_1^4 - T_2^4)}{\left[\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{F_{12} A_1} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}\right]} \qquad (1)$$

CASE

We have a vacuum jacket with area A_1 = 2.5256 m^2 at temperature T_1 = 300 K and cryogen reservoir with area A_2 = 0.5356 m^2 and T_2 = 80K. Stefan-boltzmann constant σ = 5.67*10-8 W/m^2-k^4 and emissivities at temperature 300K is ε_1=0.16 and at 80 K is ε_2=0.12. The total radiation heat transferred from vacuum jacket to cryogen reservoir is,

Substituting the values given above in equation (1),

$$\dot{Q} = \frac{\sigma(T_1^4 - T_2^4)}{\left[\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{F_{12} A_1} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}\right]}$$

$$\dot{Q} = \frac{5.67 * 10^{-8}(300^4 - 80^4)}{\left[\frac{1-0.16}{0.16 * 2.5256} + \frac{1}{1 * 0.5356} + \frac{1-0.12}{0.12 * 0.5356}\right]}$$

$$\dot{Q} = 25 \text{ W}$$

REDUCTION OF RADIATION HEAT LOAD

Multi-layer insulation (MLI) is thermal insulation composed of multiple layers of thin sheets primarily intended to reduce heat loss by thermal radiation. MLI consists of aluminium (5 to 10 nm thick) on Mylar film usually with low density fibrous material between layers with very low emissivity and high reflectivity.

Insulation must operate in vacuum where convection and conduction are much less significant and radiation dominates. MLI shouldn't be compressed too tightly usually at 30 layers/cm or else the solid conduction dominates the decrease in radiative heat transfer. Radiation heat load without shield is,

$$\dot{Q} = \frac{\sigma(T_1^4 - T_2^4)}{\left[\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{F_{12}A_1} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}\right]}$$

Radiation heat load with 1 shield is,

$$\dot{Q} = \frac{\sigma(T_1^4 - T_2^4)}{\left[\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1\varepsilon_{13}} + \frac{2(1-\varepsilon_3)}{\varepsilon_3 A_3} + \frac{1}{A_3 F_{32}} + \frac{(1-\varepsilon_2)}{\varepsilon_2 A_2}\right]}$$

In special case for which all the emissivities are same, with N shields,

$$\dot{Q}N = \frac{\dot{Q}0}{N+1}$$

Therefore to reduce 25W of heat load coming to the inner chamber to under 1W, we need at least 25 layers of Sheets. Here we have wrapped 35 layers of sheet on the surface of cryogen reservoir, bellow for side entrance, and the neck.

4.3 THERMAL DESIGN OF NECK

The heat inleak can be reduced if the evaporating vapour can be transferred through the neck, hence thereby cooling the neck taking out some of the heat load coming via conduction or radiation [8]. In case of a support or neck of cross- sectional area A and length L, let us assume that there is perfect heat exchange between the escaping gas and the neck as seen in fig.4.3, the heat balance equation is,

The Conduction heat load at a distance 'x' through length of neck is,

$$\dot{Q} = SK(T)dT/dx \qquad (1)$$

Where $\dot{Q}$ = Conduction Heat load at distance x

S = Cross − Sectional area of Pipe

$K(T)$ = Variable temperature Thermal conductivity of pipe

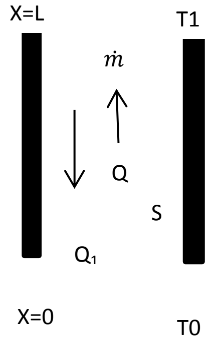


Fig 4.3 vapor precooling in neck

Also the heat removed by the gas while passing through surface of neck

$$d\dot{Q}gas = \dot{m}C_p dT \qquad (2)$$

Here, $\dot{m}$ = mass flow rate of cryogen

C_p = Specific Heat capacity at constant pressure

If perfect heat exchange takes place between gas and the neck,

$$\dot{Q} - \dot{Q}1 = \dot{m}C_p(T - T_0) \qquad (3)$$

Let us assume the thermal conductivity variation of the neck material with respect to temperature is linear i.e.

$$k(T) = K_0 + a(T - T_0) \qquad (4)$$

Here K_0 = Thermal conductivity pipe at temperature $T = T_0$

a = Constant

Substituting equation (3), (4) into (1) we get,

$$S[K_0 + a_0(T - T_0)]dT/dx = Q_1 + \dot{m}C_p(T - T_0)$$

This equation can be rearranged as,

$$\frac{[K_0 + a(T - T_0)]dT}{[Q_1 + \dot{m}C_p(T - T_0)]} = dx/s$$

Integrating L.H.S from $T = T_0$ to $T = T_1$ and R.H.S from $x = 0$ to L from partial fractions we get,

$$\frac{L}{S} = (1/\dot{m}C_p)[a\Delta T + \left(K_0 - \frac{Q_1 a}{\dot{m}C_p}\right).\ln\left(\frac{Q_1 + \dot{m}C_p\Delta T}{Q_1}\right)]$$

Where $\Delta T = T_1 - T_0$

This solution cannot be solved analytically and finding the solution through this equation is an iterative process.

CASE

We have a main dewar with Inner Diameter = 110 mm, outer diameter = 114.3 mm and length = 317.2 mm. Let the temperature at bottom $x = 0,\ T_0 = 80K$ and at top of neck $x = 317.2\ mm,\ T_0 = 300K$. Assuming the specific heat capacity (C_p) of nitrogen as 1042 J/kg-K

$$\frac{L}{S} = (1/\dot{m}C_p)[a\Delta T + \left(K_0 - \frac{Q_1 a}{\dot{m}C_p}\right).\ln\left(\frac{Q_1 + \dot{m}C_p\Delta T}{Q_1}\right)]$$

Since this equation cannot be solved analytically and it is an iterative process we have used the goal seek function in MS Excel to find the solution of above case by varying mass flow rate or Evaporation rate of fluid as seen in table 4.1. The reduction in heat load through the neck is greatest for larger values of the ratio of sensible heat to latent heat. This ratio is higher for Helium and not for nitrogen fluids, hence this method is effective in case of liquid helium dewars.

$\dot{m}\ (\frac{kg}{s})$	Q_1 (W)	$Q_1 + Q_r(W)$	$Q_r(W)$
1.00E-13	6.1637282	6.1637E+00	2.2924E-08
1.00E-12	6.1538673	6.1539E+00	2.2924E-07
1.00E-11	6.1451981	6.1452E+00	2.2924E-06
1.00E-10	6.1449126	6.1449E+00	2.2924E-05
1.00E-09	6.1447857	6.1450E+00	2.2924E-04
1.00E-08	6.1436601	6.1460E+00	2.2924E-03
1.00E-07	6.1322852	6.1552E+00	2.2924E-02
1.00E-06	6.0192766	6.2485E+00	2.2924E-01
5.00E-06	5.5306858	6.6769E+00	1.1462E+00
1.00E-05	4.9520405	7.2444E+00	2.2924E+00
2.50E-05	3.4373578	9.1684E+00	5.7310E+00
5.00E-05	1.6550918	1.3117E+01	1.1462E+01
7.50E-05	0.6825247	1.7876E+01	1.7193E+01
1.00E-04	0.2475379	2.3172E+01	2.2924E+01

4.1: Heat load coming through the neck from Conte theory

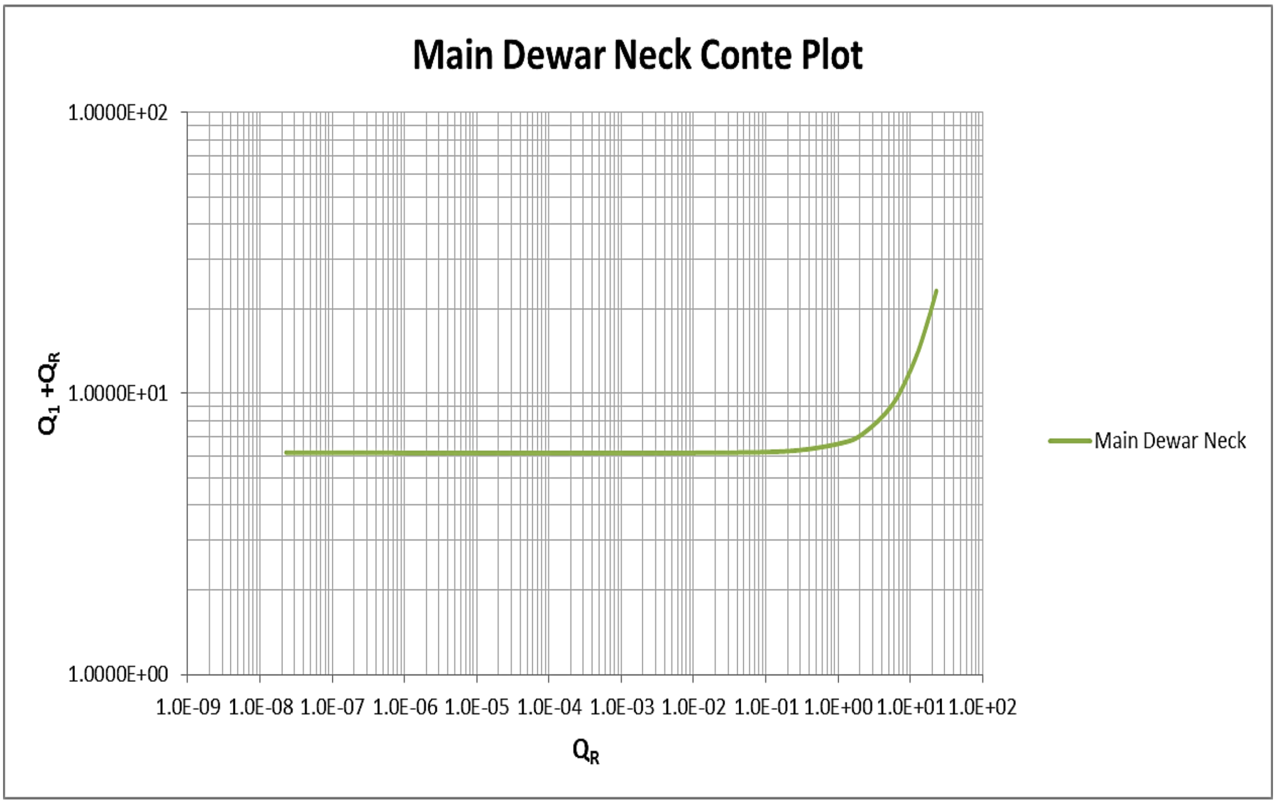


Fig. 4.4 Main Dewar Neck Conte Plot

4.4 EVAPORATION RATE AT MAXIMUM LOAD:

Maximum heat load possible = 9 W

Latent Heat of Evaporation = 200 J/g

Therefore the Evaporation Rate is,

= 9 J/s / 200 J/g = 0.045 g/s or 162 g/hr

Density of LN2 at 80 K = 790 g/Ltr

Evaporation rate of liquid Nitrogen = 162 g/hr / 790 g/Ltr

= 5 Ltr/day

4.5 EVAPORATION RATE UNDER VACUUM LEAK CONDITION

Heat load with vacuum leak is calculated using physics division cryogenic safety manual from Argonne national laboratory.

The convective heat transfer coefficient h_c is given by (from Heat Transmission, W. H. McAdams, McGraw-Hill, NY (1942) [10].

$$\frac{h_c L}{k_f} = \frac{1}{2}[\left(\frac{L^3 \rho_f^2 g \Delta T}{\mu_f^2 T_f}\right)\left(\frac{C_p \mu_f}{k_f}\right)]\text{^}0.25$$

Or

$$h_c = \frac{1}{2}\left[\left(\frac{k_f^3 \rho_f^2 g C_p}{\mu_f T_f}\right)\right]^{0.25} \times [\left(\frac{\Delta T}{L}\right)]\text{^}0.25$$

Where k_f = Thermal conductivity, ρ_f = Density, μ_f = Viscosity, C_p = Specific heat

T_f = Average temperature, ΔT = Temperature Difference

In our case we have a vacuum jacket sitting at 300K and a cryogenic reservoir at 80 K. If there is a leak through the jacket the reservoir would be exposed to air at atmospheric conditions. So the convective load coming on the cryogen reservoir can be found out using the formula given above. The subscript 'f' means the quantities are to be evaluated at the "gas film" temperature, the arithmetic means of the temperature at the surface of the solid, and the temperature of the bulk of the gas and L is the characteristic dimension of the system.

To use this formula first we have find the values of all the parameters at average temperature

$$T_f = \frac{300+80}{2} = 190K$$

$$\Delta T = 300 - 80 = 220K$$

Now the values of parameter at $T_f = 190K$ are,

$$k_f = 1.8 \times 10^{-4}\ W/cm.K,\ \ \rho_f = 1.8 \times 10^{-3} g/s,\ \ \mu_f = 120 \times 10^{-6}\ Poise$$

$$C_p = 1.04 \frac{J}{g.K},\ g = 980\ cm/s^2$$

Substituting these values in equation 2 we get,

$$h_c = \frac{1}{2}\left[\left(\frac{1.8 \times 10^{-12} \times 1.8 \times 10^{-6} \times 980 \times 1.04}{120 \times 10^{-6} \times 190}\right)\right]^{0.25} \times [\left(\frac{220}{27.3.}\right)]\text{^}0.25$$

$$h_c = 8.075 \times 10^{-4}\ \mathrm{W/cm^2.K}$$

Heat flow Q is given by,

$$Q = h_c \Delta T$$

$$Q = 8.075 \times 10^{-4} \times 220$$

$$Q = 0.1776\ \mathrm{W/cm^2}$$

Now the total heat transferred to the cryogen reservoir is,

$$\dot{Q} = Q \times A$$

$$\dot{Q} = 0.1776 \times 5356 = 952\ \mathrm{W}$$

Therefore the Evaporation rate with vacuum leak comes out to be,

$$\dot{m} = \dot{Q}/h_{fg}$$

$$\dot{m} = \frac{960}{200} = 4.80\frac{g}{s} = \frac{4.8}{1142} = 0.0042\frac{m^3}{s} = 0.252\ m^3/\mathrm{min}$$

4.6 C_v OF RELIEF VALVE

The capacity coefficient of relief valve has to be calculated so that it can handle the maximum flow rate at nitrogen through it under vacuum leak condition. In the last topic we calculated the maximum flow rate possible under vacuum leak condition if this flow is not relieved the pressure inside the cryogen reservoir will continue to build which can lead to a catastrophe.

Flow through the relief valve can be divided in o two conditions

1. For Normal flow critical ratio $\frac{P_1}{P_2} < 1.89$
2. For Choked flow critical pressure ratio $\frac{P_1}{P_2} > 1.89$

Flow Rate (SCFM) for Normal Flow,

$$Q = 16.05 \times C_v \times \sqrt{\left[\frac{P_1^2 - P_2^2}{T(°R) \times S_g}\right]}$$

Flow Rate (SCFM) for Choked Flow,

$$Q = 13.63 \times C_v \times P_1 \sqrt{\left[\frac{1}{T(°R) \times S_g}\right]}$$

To calculate Cv for nitrogen,

$S_g = 0.967, P_1 = 36.26 \text{ Psi}, P_2 = 14.7 \text{ Psi}, T(°R) = 540 \text{ and } Q = 8.9 \text{ ft}^3/\text{min}$

$$\frac{P_1}{P_2} = \frac{36.26}{14.5} = 2.5 > 1.89$$

Hence the flow through the relief valve is choked flow, for this calculating the C_v for mass flow rate at vacuum leak condition.

$$Q = 13.63 \times C_v \times P_1 \times \sqrt{\left[\frac{1}{T(°R) \times S_g}\right]}$$

$$8.9 = 13.63 \times C_v \times 36.26 \times \sqrt{\left[\frac{1}{540 \times 0.967}\right]}$$

Therefore C_v for relief valve is, $C_v = 0.418$

4.7 CONDENSATION ON THE COLD HEAD SURFACE

Condensation occurs when the temperature of a vapor is reduced below its saturation temperature T_{sat}. In this case it is done by bringing the vapor into contact with a solid surface which is cold heads heat exchange whose temperature T_s is below the saturation temperature T_{sat} of the vapor.

The type of condensation that takes place in this case is film condensation; the condensate wets the surface and forms a liquid film on the surface that slides down under the influence of gravity. The thickness of the liquid film increases in the flow direction as more vapors condense on the film as in fig.4.5.

Here the condensation rate calculations were done with the help of Nusselt analysis on laminar film condensation and turbulent film condensation with the assumption taken as,

I. Both the plate and the vapor are maintained at constant temperatures of Ts = 79 K and Tsat = 81 K, respectively, and the temperature across the liquid film varies linearly.
II. Heat transfer across the liquid film is by pure conduction (no convection currents in the liquid film).

An excel programme was generated to find the Reynolds number of the condensate flow in order to check if it was laminar (Re<30), wavy laminar (30<Re<1800) and turbulent (Re>1800). With the data taken for liquid and gaseous nitrogen from Gaspack software at 80K temperature it was found out the condensate flow was in wavy laminar region.

For the Wavy Laminar region the Reynolds number is,

$$\mathrm{Re} = \left[4.81 + \frac{3{,}7 \times \mathrm{L} \times \mathrm{K_l} \times (\mathrm{T_{sat}} - \mathrm{T_s})}{\mu_l \times h'_{fg}} \left(\frac{g}{\nu_l^2}\right) \hat{} \left(\frac{1}{3}\right)\right]^{0.82}$$

Where, ρ_l= Density of fluid ρ_v = Density of vapour

μ_l = Dynamic viscosity of liquid k_l = Thermal Conductivity of liquid

A = Surface area L = length

h_{fg} = Latent heat of vaporisation h'_{fg} = modified Latent heat of vaporisation

Since $\rho_v \ll \rho_l$

$$Re = 66.52$$

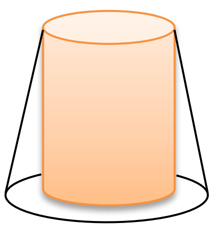


Fig. 4.5 Condensation on a vertical cylinder

Now to calculate the surface heat transfer coefficient

$$h_l = \frac{Re \times \mu_l \times h'_{fg}}{4 \times L \times (T_{sat} - T_s)}$$

$$h_l = 3339\ \mathrm{W/m^2K}$$

The heat transfer through the film layer for condensation of vapours is,

$$\dot{Q} = h_l \times A \times (T_{sat} - T_s)$$

In this equation either we can fix the area and calculate the condensate flow rate or we can fix the heat transfer rate to calculate the area require for the condensation to take place.

Case I: Calculating the condensation rate of liquid nitrogen using the peripheral area of the heat exchange with dimensions OD = 0.1 m and Length = 0.067 m.

$$\dot{\mathrm{Q}} = 3339 \times \Pi \times 0.1 \times 0.067 \times (81 - 79)$$

$$\dot{\mathrm{Q}} = 140\ \mathrm{W}$$

Therefore the condensation rate, $\dot{\mathrm{m}} = \dot{\mathrm{Q}}/\mathrm{h}'_{\mathrm{fg}}$

$$\dot{\mathrm{m}} = \frac{140}{197814.4} = 0.71\ \mathrm{g/s}$$

In actual case 140 W may not be available for condensation of nitrogen gas. Since the cryocooler produces 266 W at 80 K almost half of the refrigeration capacity goes for removing sensible heat from the gas except in the case where regenerator part of the cold head is used for precooling of nitrogen gas.

Case II: In this case the data is taken from the one of the experimental runs where regenerator precooling is not used and also no condensers for extra area for condensing gases and the area is found out for the condensation of nitrogen gas.

In the experimental run the condensation rate was found to be 0.62 g/s hence the heat transferred for condensing nitrogen gas is,

$$\dot{\mathrm{Q}} = \dot{m} \times \mathrm{h}'_{\mathrm{fg}}$$

$$\dot{\mathrm{Q}} = 0.62 \times 10^{-3} \times 197814.4 = 123\ \mathrm{W}$$

Therefore calculating the surface area required for condensation is,

$$\dot{\mathrm{Q}} = \mathrm{h_l} \times \mathrm{A} \times (\mathrm{T_{sat}} - \mathrm{T_s})$$

$$123 = 3339 \times \mathrm{A} \times (81 - 79)$$

$$A = 0.018\ m^2$$

For the heat exchange the effective length with OD = 0.1m turns out to be 0.057m. This means the bottom part and some of the peripheral part is used for precooling.

CHAPTER 5

MECHANICAL DESIGN OF DEWAR

5.1 INTRODUCTION

Dewar can be constructed with material like Stainless steel, Glass (known as Glass dewars) etc. The most common material used in cryogenic industry is Stainless Steel 304 (SS 304) mainly because of its low thermal conductivity and higher strength. The other important feature of SS 304 is it can be easily electropolished to provide clean oxidation free surface and with less contaminants, since electropolishing minimizes effective surface area for the capture of gas by adsorption. Stainless steel can be easily welded with Tungsten Inert Gas welding to provide vacuum tight welded joints for high and ultra high vacuum processes. The only drawback of using SS 304 is the weight of the material where it is of major concern.

Taking into account the strengths of SS304 and the availability of the material it is an ideal choice for fabricating a dewar for experimental and commercial purpose.

5.1.1 PARTS SIZING FOR STRENGTH

Often dewar have to tolerate Pressure above atmospheric and below atmospheric, so we need to calculate the size of the parts on the basis of mechanical considerations. Basically we can follow four general guidelines while designing a dewar for mechanical strength.

1. Dimension of critical component to keep expected stress to half of the materials yield strength.
2. Walls of the tube should be thick enough to avoid buckling in case of subjected to compression strength.
3. Thickness of the dewar walls to withstand maximum loading they will experience from pressurization.
4. Limit deflection to acceptable level.

To fabricate dewar basically we need to design for vacuum jacket, cryogen reservoir and the neck which supports the cryogen reservoir to vacuum jacket.

5.2 DESIGN OF NECK OF A DEWAR

Neck is a critical component for mechanical and thermal aspect of designing a dewar. It is part which supports the cryogen reservoir to vacuum jacket. It is basically a hollow pipe which can house the cold head of GM cryocooler in dewar. The only way neck could fail is due to tensile load of cryogen reservoir acting on it.

In this case we have chosen a SS 304 hollow pipe of 4” SCH 10S from range of pipes available in IUAC, Since the pipe is little bit thick the conduction load coming to the cryogen reservoir is high. To reduce the conduction load we removed 1.5 mm of material for 75 mm along the length of neck. The critical load will be generated on the thinner section of the neck.

Inner Diameter of SS tube $D_i = 108.2$ mm

Outer Diameter of SS tube $D_o = 114.3$ mm and minimum outer diameter $D'_o = 111.3$ mm

Length of Tube $L = 320$ mm

The tensile load acting on this tube is of cryogen reservoir of weigh approximately 15 kgs or 150 N of load. Let us take the factor of safety as 2 for a safe design.

$$\frac{\sigma_t}{f.o.s} = \frac{F}{A_c}$$

Here $\sigma_t = \text{Tensile strenght of material}$

$F = \text{load acting on neck}$

$A_c = \text{Cross} - \text{sectional area of neck}$

$f.o.s = \text{Factor of safety}$

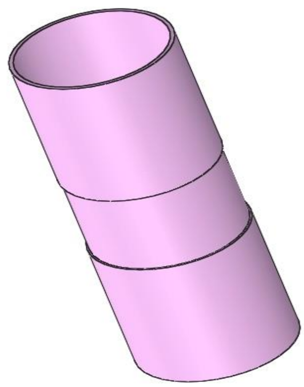


Fig. 5.1 3D model of Neck

From the above equation we can find the strength of the material under these conditions and compare it with the tensile strength of material.

$$\frac{\sigma_t}{f.o.s} = \frac{F}{A_c}$$

$$\frac{\sigma_t}{2} = \frac{150 \times 4}{\Pi \times (0.1113^2 - 0.1082^2)}$$

$$\sigma_t = 561352\ \mathrm{N/m^2}$$

Tensile strength of SS 304 = 515 MPa (minimum) i.e. 515E6 N/m^2, the value we got is well under the required tensile strength of SS 304, hence the design is safe.

5.3 DESIGN OF CRYOGEN RESERVOIR

Cryogen reservoir is a vessel where the cryogen after getting condensed on the cold head is collected. Its function is to store the cryogen liquid with as less heat load as possible for less evaporation rate of cryogen. This vessel will be pressure loaded upto 1 bar g, hence the container walls and the end plates need to be thick enough to handle axial and hoop stress which should be less than the yield strength of the material.

Cylinder hoop Stress along its circumference, $\sigma_{hoop} = P \times r/t$

Cylinder axial stress along its length, $\sigma_{axial} = P \times r/2t$

Where, P = Pressure inside or outside the cylinder

r = Diameter of the cylinder where pressure is acting

t = Thickness of pipe

Dimensions of the cryogen reservoir

Pipe- 10" SCH 10S

Outer Diameter = 273 mm

Inner Diameter = 267 mm

Length of pipe = 500 mm

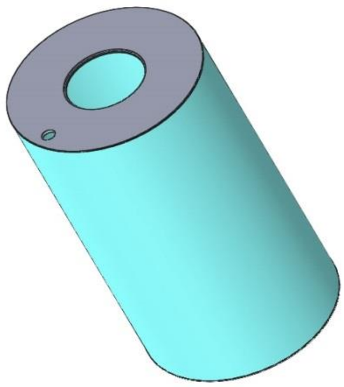


Fig. 5.2 3D model of Cryogen Reservoir

The working pressure of our system is around 0.5 bar g which can go upto 1 bar g maximum afterwards a 15 psi rated relief valve opens to relieve the pressure build up inside the reservoir.

Calculating the pressure this vessel can handle using the dimension above for the yield stress of SS304 $\sigma_{yt} = 240\ MPa$ with factor of safety 2.

Cylinder hoop Stress, $\sigma_{hoop} = P \times r/t$

$$\frac{\sigma_{yt}}{2} = P \times r/t$$

$$\frac{240 \times 10^6}{2} = P \times 0.1335/0.003$$

$$P = 27 \text{ bar}$$

This pipe can handle 27 bar of pressure with factor of safety 2; hence its dimensions are safe. As we know axial stress for a pressure vessel is half of the hoop stress therefore it can handle twice the pressure for this dimension.

Calculating the maximum allowable internal pressure inside a vessel for a circular flat bottom welded plate.

End Plate Dimension

Diameter = 273 mm

Thickness = 7 mm

Maximum Pressure limit for End circular plate,

$$t^2 = 0.75 \times r^2 \times (\frac{P}{\sigma_{yt}})$$

$$49 = 0.75 \times 136^2 \times (\frac{P}{12})$$

$$P = 4.3 \text{ bar}$$

This vessel can handle 4.3 bar of pressure with factor of safety 2; hence its dimensions are safe.

5.4 DESIGN OF VACUUM JACKET

Designing for Vacuum applications are just the inverse of the internal pressure situation, with the outside pressure trying to implode the tube. The same hoop and axial stress formulas apply. Here we have to use a more conservative factor of safety value which almost 25 % of the tensile strength of material used.

Cylinder hoop Stress along its circumference, $\sigma_{\mathrm{hoop}} = \mathrm{P} \times \mathrm{r}/\mathrm{t}$

Cylinder axial stress along its length, $\sigma_{\mathrm{axial}} = \mathrm{P} \times \mathrm{r}/2\mathrm{t}$

Where, P = Pressure inside or outside the cylinder

r = Diameter of the cylinder where pressure is acting

t = Thickness of pipe

The vacuum jacket in our case has two pipes of size 12”SCH10S and 25”SCH10S with thickness 4.57 and 8 mm respectively, Now calculating the stress it can handle for 60 MPa of yield stress.

Cylinder hoop Stress along its circumference, $\sigma_{\mathrm{hoop}} = \mathrm{P} \times \mathrm{r}/\mathrm{t}$

$$60 = \mathrm{P} \times 0.162/0.0047$$

$$\mathrm{P} = 1.74\ \mathrm{MPa}$$

Now for 25”SCH10S pipe

Cylinder hoop Stress along its circumference, $\sigma_{\mathrm{hoop}} = \mathrm{P} \times \mathrm{r}/\mathrm{t}$

$$60 = \mathrm{P} \times 0.333/0.008$$

$$\mathrm{P} = 1.44\ \mathrm{MPa}$$

The pressure this vessel can handle is well above the required criteria of 0.1 MPa hence there is no chance of buckling under the pressure from atmospheric conditions for both the pipes.

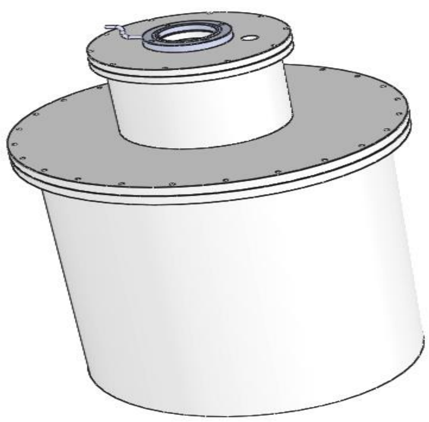


Fig. 5.3 3D model of Vacuum Jacket

CHAPTER 6

FABRICATION AND ASSEMBLY OF DEWAR

6.1 FABRICATION OF EXPERIMENTAL DEWAR

Liquid Nitrogen Dewar is a cryogenic vessel used to store liquid nitrogen. Liquid nitrogen dewar usually consist of a vessel surrounded by vacuum jacket which isolates vessel from atmospheric environment. The cryogen reservoir is super insulated to reduce the radiation heat load. As per the availability of materials and pipes at IUAC dewar was designed for thermal and mechanical stability. The main parts of experimental dewar were;

1. Cryogen Reservoir Assembly: - It is vessel with OD 273 mm, wall thickness 3 mm and length 500 mm which is TIG welded with two endplates of thickness 5 mm each to make a vessel of 28 Ltr capacities. Top end plate is again TIG welded with neck to support the vessel with vacuum jackets top flange. Top end plate also consist an offset hole of OD 19.1 mm at 115 mm from the centre of the plate for the bellow assembly to be welded with it to produce another entry point for nitrogen gas.

   This assembly was leak tested with MSLD (Mass spectrometry Leak Detector) for any leaks. The Helium leak tightness was $<1*10^{-10}$ mbar Ltr/sec at $4.3*10^{-2}$ mbar which is acceptable in dewars. This assembly was subjected to cold shock test using liquid nitrogen at all the welds. Subjecting SS 304 to low temperatures could reveal some welding defects if present due to the thermal contraction and expansion of stainless steel at low temperature (77 K) to atmospheric conditions 300 K. It was then again tested for any leaks.

Fig: 6.1 Welding and leak test of the cryogen reservoir assembly

2. Bellow Assembly: - This was one of the most crucial parts in terms of assembling and welding because of the presence of small parts like 1 inch Tee, Conflict Flanges (CF 25), Bellow and an adaptor to connect the 1 inch tee with bellow to the reservoir. This arrangement was fabricated to get access for level sensor, Temperature sensor for cold head, a 300W heater and side inlet for nitrogen.

   At first the CF 25 flanges were welded to the 1 inch tee. This assembly was welded to adaptor and then to the ½ inch bellow. The bellow was welded with a ½ inch pipe of certain length so it can be welded to top end plate of the cryogen reservoir, but first the tee assembly was leak tested with MSLD before and after the cold test as seen in fig.6.2. The Helium leak tightness was in the range of 10^{-10} mbar Ltr/s. The adaptor was then welded to top flange of the vacuum jacket and pipe with the top end plate of cryogen reservoir.

Fig: 6.2 Welding and cold shock test of the bellow assembly

3. Vacuum Jacket: - As we have discussed it is a vessel surrounding the cryogen reservoir to protect liquid cryogen from atmospheric conditions. An open container with OD 666 mm, thickness 8 mm and length 685 mm was available with square O-Ring which made the basis of the jacket design.

   A pipe with OD 323 mm, thickness 4.5 mm and length 320 mm was machined to get the required height and clearance to accommodate the cryogen reservoir and the neck assembly. One end of this pipe is welded to a flange with 12

M10 through holes and an O-ring groove to form a vacuum seal with top plate of jacket of thickness 20 mm with 12 M10 through holes and the other end is welded to another plate of OD 750 mm and thickness 25 mm which is bolted to the container. A ¼ inch pipe was welded with the vacuum jacket to provide inlet for nitrogen gas through neck of dewar.

Fig: 6.3 Welding and assembly of the vacuum jacket

6.2 ASSEMBLY OF THE DEWAR

All the joints were TIG welded, cleaned with scrubber and alcohol and the O-rings were placed in respective O-ring grooves. The reservoir assembly was assembled with vacuum jacket and bolted to form a vacuum seal with the O-rings. This assembly was then tested for leaks between cryogen reservoir and the jacket with MSLD. At first the vacuum didn't receded below 10 mbar due to a pinhole leak present at the weld between adaptor and the top flange of jacket. This joint was again welded and the setup was again tested for any leaks. MSLD revealed no leaks inside dewar and the vacuum receded in low 10^{-2} mbar range.

Multi-layer insulation was wrapped on the cryogen reservoir, neck and the bellow part to reduce the heat influx due to radiation. Upto 35 layers of Aluminium sheets were wrapped on the cryogen reservoir to reduce maximum 25 W of radiation load coming on the reservoir once its filled upto the brim and 15 layers on the neck and the bellow since they are also subjected to cool down once the cryocooler is started as seen in fig.6.4. This was the most important procedure in assembling dewar, if we wrap the layers too tightly above each other conduction and convection load between layers will increase because the air molecules would not get space to escape and high vacuum can't be achieved. Approximately 30 layers of MLI can wound on each other in 1 cm of space.

Fig: 6.4 MLI wrapping and Evacuation of the dewar

6.3 CONDENSERS

Two types of copper condensers were fabricated with the help of Vacuum Techniques Pvt. Ltd. one with short fins and the other with long fins but the number of fins were lesser in the latter to have same amount of area around 0.2 m^2 available for cooling or condensing the N_2 gas. These are bolted to the cold heads heat exchange with indium foil for good thermal contact and acts as an extension of it to provide extra area for condensing gases.

Fig: 6.5 Condenser Type I- Short Fins

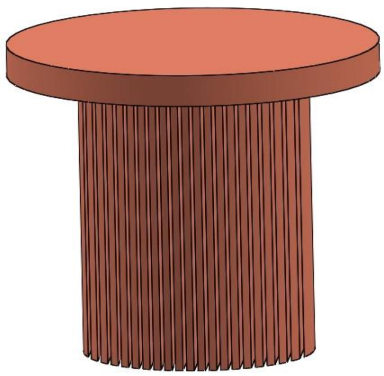


Fig: 6.6 Condenser Type II- Long Fins

CHAPTER 7

EXPERIMENTAL RESULTS AND ITS ANALYSIS

7.1 EXPERIMENTAL SETUP

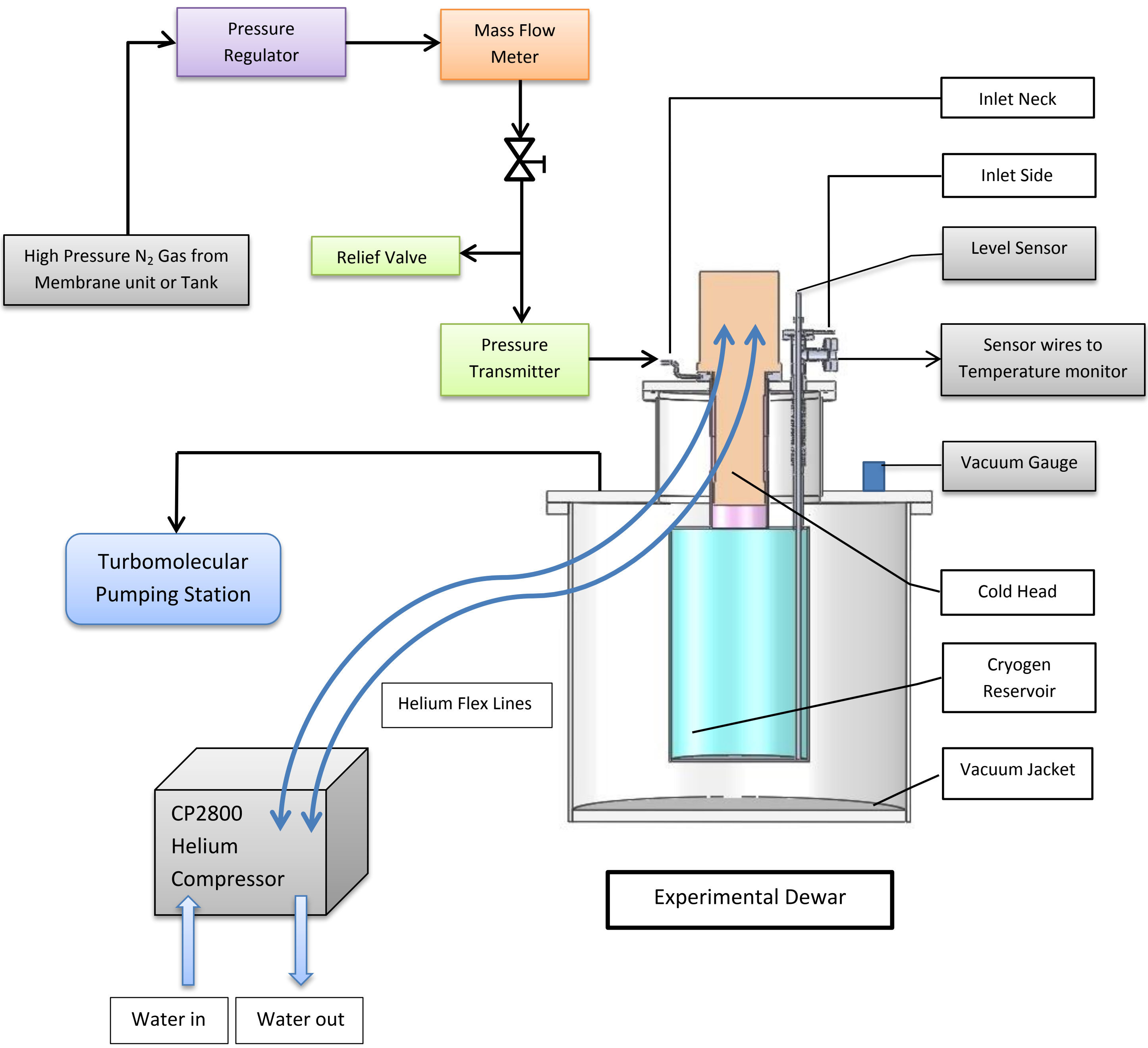


Fig: 7.1 Block Diagram of the Experimental setup

7.1.1 ARRANGEMENT OF THE SETUP

The arrangement of the setup was done as seen in the block diagram. The cold head of cryocooler was placed on top of the dewar and bolted on the flange with O-ring. The helium flex lines, motor cord, cooling water supply were fitted to compressor package. Nitrogen gas was supplied from cryogenic storage tanks at 2.5 bar g pressure through a flexible tube towards the pressure regulator. The regulator was set to a pressure of 0.5 bar g pressure at the outlet which directly goes to the inlet of mass flow meter. The ¼ inch pipe which was welded for neck inlet was fitted with a Parker made 15 Psi relief valve, pressure transmitter and a Swagelok on-off valve. This arrangement is then connected to the mass flow meter outlet.

7.1.2 OPERATION

The operation of setup was done for different cases devised to maximize the liquid nitrogen production. The setup was continually purged with high pressure N2 gas for around 5 mins to remove any water vapour or anything before starting the cryocooler, which can condense on the cold head thus giving us false data. This gas was supplied from the cryogenic tank at 2.5 bar g pressure using a flexible tube ¼ inch tube.

Once the cryocooler starts it takes around 15 mins to cool down to 80 K temperature. Then the N_2 gas inside the dewar starts to condense on the cold heads heat exchange part and drips down to the cryogen reservoir where it starts to cool the dewar. The production rate continues to increase until a steady state is reached after 3 hrs. which can also be observed with 4 temperature sensors mounted on the dewar. At steady state the production rate reaches a maximum value. Each run was done for 9 hrs. and the data was gathered for analysis.

Fig.7.2: Experimental setup in operation

7.2 EXPERIMENTAL RESULTS

7.2.1 EXPERIMENTAL RUN 1

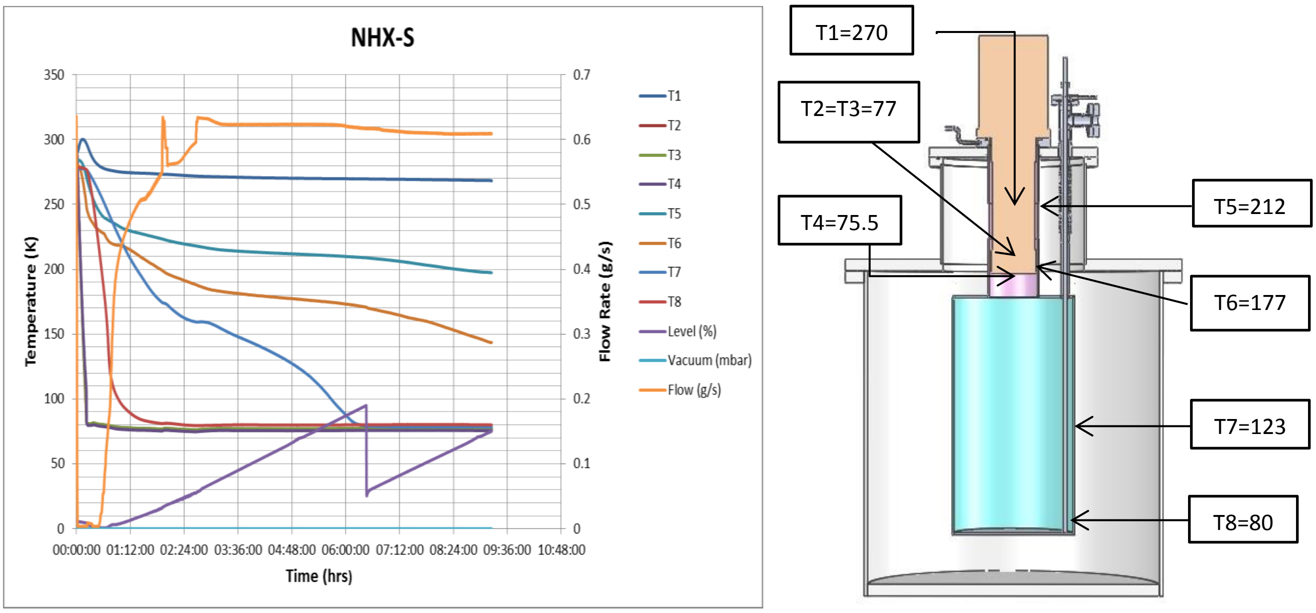


Fig.7.3: Cooldown curve and sensor data at steady state condition for Run 1

Entry N_2 Gas	Side Port
Operating Pressure	0.35 bar g @ Steady State
Production Rate	68.1 Ltr/day @ Steady State
Condenser	N.A
Observations	➢ N_2 gas had to be precooled and condensed by the cold head due to side entry of gas hence no involvement of regenerator part. ➢ From the sensor data we can see T4 is lower than T2 & T3 and fluctuating, which means the bottom part of heat exchanger is being used for cooling N_2 gas and side part for condensation. ➢ Cryocooler cools down to 80 K in 15 mins and the dewar achieve steady state in around 3 hrs. ➢ Maximum production rate of 68.1 Ltr/day was achieved at steady state condition which can be seen from sensors T1 to T6 around 3 hrs. after starting the cryocooler. ➢ The capacity of cryocooler is 266 W @ 80 K and enthalpy to cool and condense N_2 at 0.5 bar g from 300 K to 80 K is 427 J/g which gives us a production rate of 68.5 Ltr/day.

7.1 Observation table for run 1

7.2.2 EXPERIMENTAL RUN 2

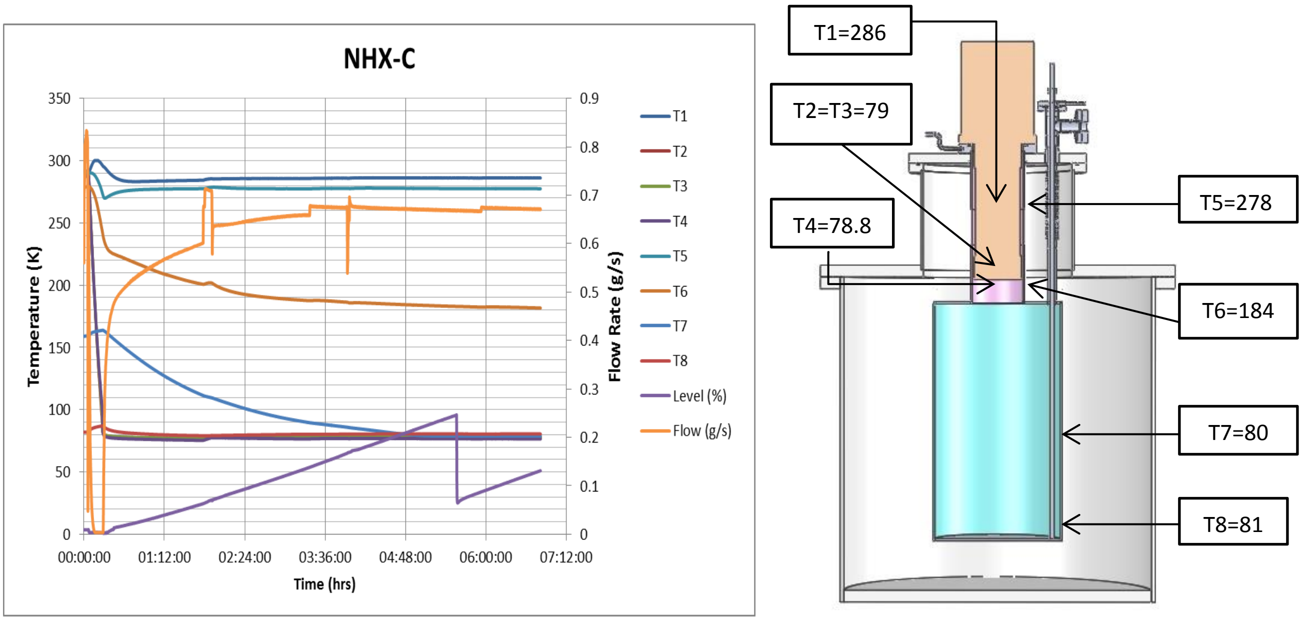


Fig.7.4: Cooldown curve and sensor data at steady state condition for Run 2

Entry N_2 Gas	Neck Port
Operating Pressure	0.47 bar g @ Steady State
Production Rate	73.4 Ltr/day @ Steady State
Condenser	N.A
Observations	➢ N_2 gas flow through the space between cold head and neck of dewar. The temperature profile changes dramatically in neck when warm fluid flows through it. ➢ From the sensor data we can see T4 is lower than T2 & T3 which means the bottom part is being used for cooling N_2 gas. ➢ Maximum production rate of 73.4 Ltr/day was achieved at steady state condition which can be seen from sensors T1 to T6 around 3 hr after starting the cryocooler. ➢ Some amount of enthalpy is taken out by the regenerator from N2 gas since the temperature varies from 290 K to 80 K till the gas reaches heat exchanger part of cold head. ➢ The capacity of cryocooler is constant at 266 W with this the maximum achievable production rate is 68.4 Ltr/day but it is 73.4 Ltr/day which proves the precooling effect of gas.

7.2 Observation table for run 2

7.2.3 EXPERIMENTAL RUN 3

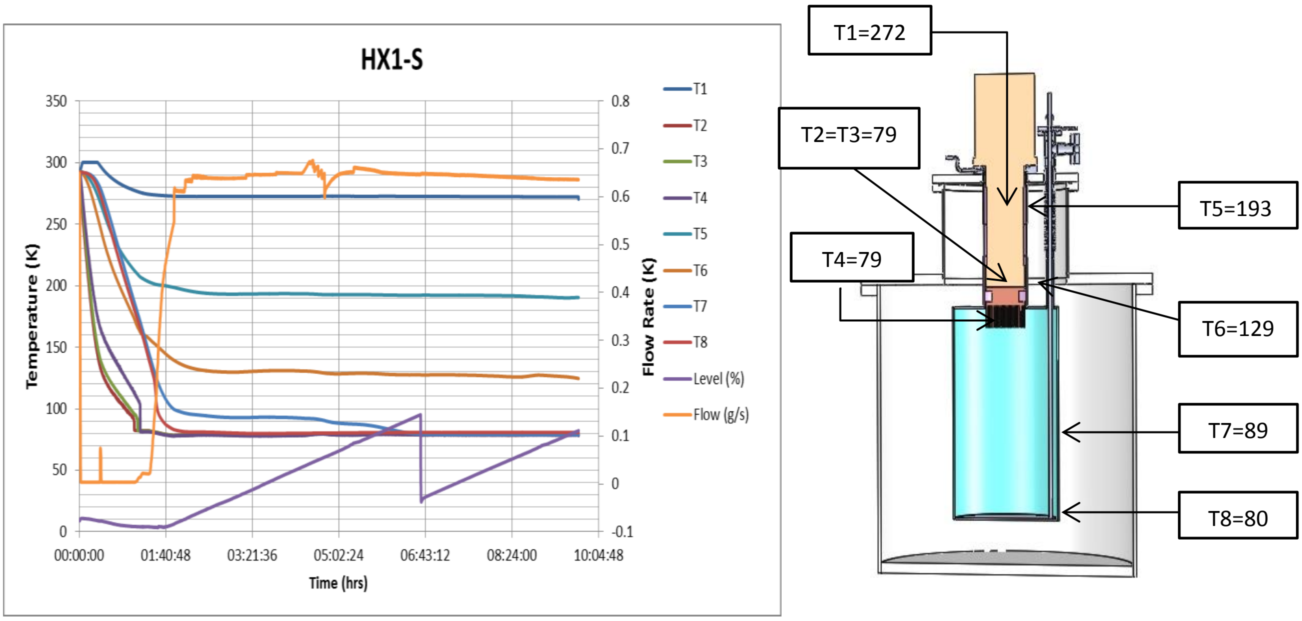


Fig.7.5: Cooldown curve and sensor data at steady state condition for Run 3

Entry N_2 Gas	Side Port
Operating Pressure	0.44 bar g @ Steady State
Production Rate	70.4 Ltr/day @ Steady State
Condenser	Type I (HX1) (Short Fins)
Observations	➢ Around 0.2 m^2 of extra area for precooling and condensation.N_2 gas. The production rate achieved here proves that the area available for cooling of gas was not enough in experiment run 1. ➢ From the sensor data we can see T2, T3, T4 are almost equal so it is difficult to predict if the condenser is fully or partially involved in condensation of N_2 gas. ➢ Maximum production rate of 70.4 Ltr/day was achieved at steady state condition which can be seen from sensors T1 to T6 around 3 hrs. after starting the cryocooler. ➢ The capacity of cryocooler is 275 W @ 80 K with condenser which we got from capacity test of cryocooler and enthalpy to cool and condense N_2 at 0.5 bar g from 300 K to 80 K is 427 J/g which gives us a production rate of 70.4 Ltr/day.

7.3 Observation table for run 3

7.2.4 EXPERIMENTAL RUN 4

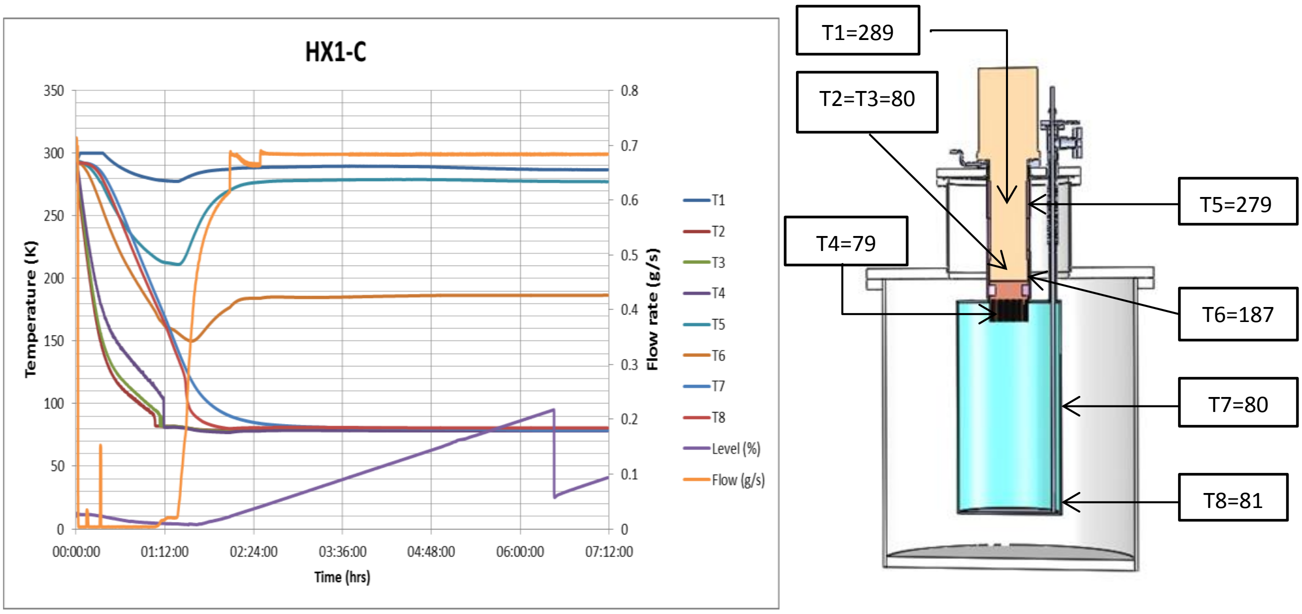


Fig.7.6: Cooldown curve and sensor data at steady state condition for Run 4

Entry N_2 Gas	Neck Port
Operating Pressure	0.47 bar g @ Steady State
Production Rate	74.7 Ltr/day @ Steady State
Condenser	Type I (HX1) (Short Fins)
Observations	➢ Around 0.2 m^2 of extra area for precooling and condensation of N_2 gas. ➢ From the sensor data we can see T4 is lower than T2 & T3 which means the bottom part is being used for cooling N_2 gas. ➢ Maximum production rate of 74.7 Ltr/day was achieved at steady state condition which can be seen from sensors T1 to T6 around 3 hr after starting the cryocooler. ➢ Some amount of enthalpy is taken out by the regenerator from N_2 gas since the temperature varies from 290 K to 80 K till the gas reaches heat exchanger part of cold head. ➢ The capacity of cryocooler is constant at 275 W with this the maximum achievable production rate is 68.4 Ltr/day but it is 74.7 Ltr/day which proves the precooling effect of gas.

7.4 Observation table for run 4

7.2.5 EXPERIMENTAL RUN 5

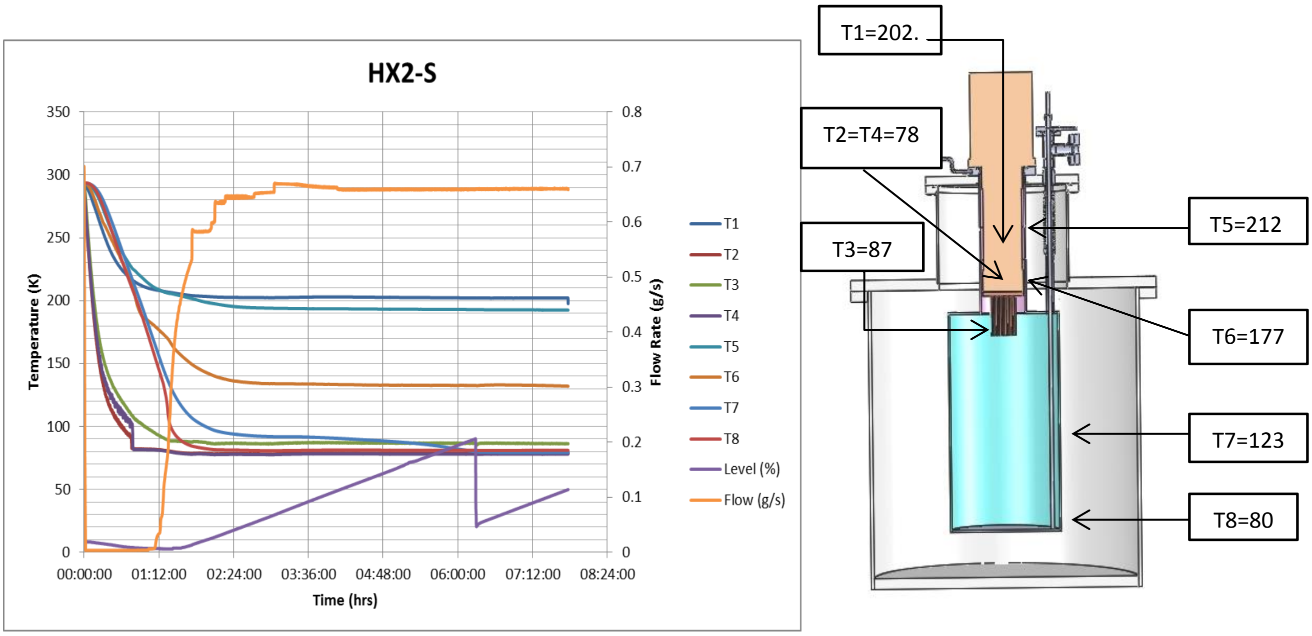


Fig.7.7: Cooldown curve and sensor data at steady state condition for Run 5

Entry N_2 Gas	Side Port
Operating Pressure	0.51 bar g @ Steady State
Production Rate	71 Ltr/day @ Steady State
Condenser	Type II (HX2) (Long Fins)
Observations	➢ Around 0.2 m^2 of extra area for precooling and condensation.N_2 gas. The production rate achieved here proves that the area available for cooling of gas was not enough in experiment without condenser. ➢ From the sensor data we can see T3 is higher than T2 & T4 which means that bottom part of condenser is being used for cooling N_2 gas and side part for condensation. ➢ Maximum production rate of 71 Ltr/day was achieved at steady state condition which can be seen from sensors T1 to T6 around 3 hrs. after starting the cryocooler. ➢ The capacity of cryocooler is 275 W @ 80 K with condenser which we got from capacity test of cryocooler and enthalpy to cool and condense N_2 at 0.5 bar g from 300 K to 80 K is 427 J/g which gives us a production rate of 71 Ltr/day.

7.5 Observation table for run 5

7.2.6 EXPERIMENTAL RUN 6

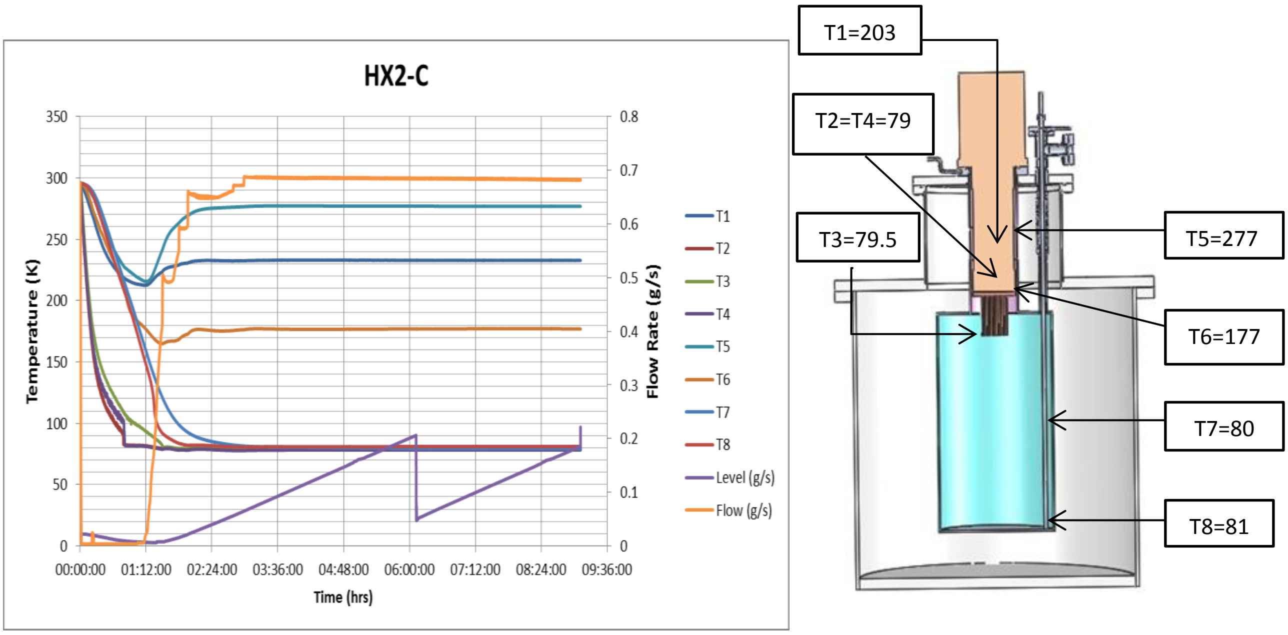
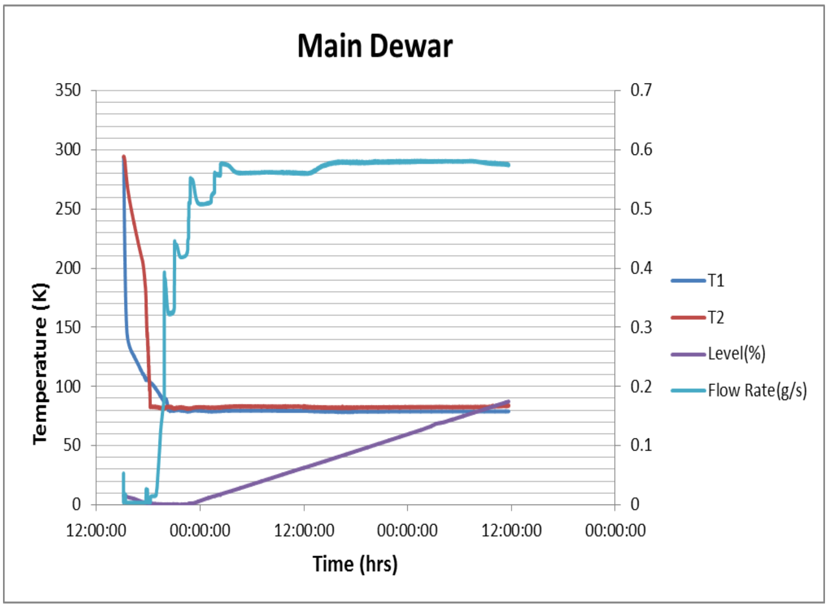


Fig.7.8: Cooldown curve and sensor data at steady state condition for Run 6

Entry N_2 Gas	Neck Port
Operating Pressure	0.55 bar g @ Steady State
Production Rate	75 Ltr/day @ Steady State
Condenser	Type II (HX2) (Long Fins)
Observations	➢ 0.2 m^2 of extra area for cooling and condensation N_2 gas. ➢ From the sensor data we can see T4 is lower than T2 & T3 which means the bottom part is being used for cooling N_2 gas. ➢ Maximum production rate of 75 Ltr/day was achieved at steady state condition which can be seen from sensors T1 to T6 around 3 hr after starting the cryocooler. ➢ Some amount of enthalpy is taken out by the regenerator from N_2 gas since the temperature varies from 290 K to 80 K till the gas reaches heat exchanger part of cold head. ➢ There is no theoretical formulation to predict the enthalpy removed but it can be predicted by CFD simulations. ➢ The capacity of cryocooler is constant at 275 W with this the maximum achievable production rate is 68.4 Ltr/day but it is 75 Ltr/day due to the precooling effect of cold head.

7.6 Observation table for run 6

7.2.7 MAIN DEWAR



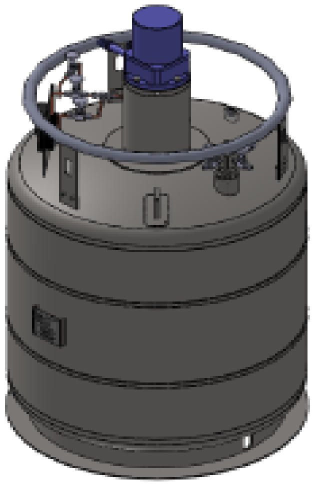


Fig.7.9: Cooldown curve and sensor data at steady state condition for Main dewar run

Entry N_2 Gas	Neck Port
Operating Pressure	0.45 bar g @ Steady State
Production Rate	64 Ltr/day @ Steady State
Condenser	Type II (HX2) (Long Fins)
Observations	➢ Around 0.2 m^2 of extra area for precooling and condensation.N_2 gas. ➢ From the sensor T1 at condenser and T2 at the bottom of dewar we can see that it takes around 12 hrs. for the dewar to attain steady state condition. ➢ Maximum production rate of 64 Ltr/day was achieved at steady state condition which can be seen from sensors T1 to T2 around 12 hrs after starting the cryocooler. ➢ Some amount of enthalpy is taken out by the regenerator from N_2 gas since the temperature varies from 290 K to 80 K till the gas reaches heat exchanger part of cold head. ➢ In the experimental results we got maximum production rate of 74 Ltr/day in this configuration, but due to high radiation load the production rate was reduced to 64 Ltr/day.

7.7 Observation table for Main dewar run

7.8 Summarised data of the experimental runs

Run	Entry	T1 (K)	T2 (K)	T3 (K)	T4 (K)	T5 (K)	T6 (K)	T7 (K)	T8 (K)	Pressure (bar g)	Vacuum (mbar)	Production Rate (Ltr/day)
1	Side	270.1	76.9	77.1	75.5	211.6	176.8	122.9	79.9	0.35	2.4E-5	68.1
2	Neck	286.1	78.0	78.3	76.8	277.7	183.9	79.3	80.6	0.47	2.1E-5	73.4
3	Side HX1	272.6	79.0	79.0	78.8	192.6	128.3	88.4	80.3	0.44	2.3E-5	70.4
4	Neck HX1	288.7	79.7	79.0	78.3	278.7	186.4	79.8	80.6	0.47	2.2E-5	74.7
5	Side HX2	202.5	78.7	86.9	78.1	193.2	132.8	87.9	81.1	0.51	2.2E-5	71
6	Neck HX2	232.9	78.8	79.5	78.2	277.0	176.7	79.9	80.9	0.55	2.1E-5	75

7.3 CFD MODELLING

7.3.1 VAPOUR PRECOOLING OF DEWAR NECK

As we have seen in thermal designing of neck the sensible heat of evaporating N_2 vapours can be used to remove some of the enthalpy coming via conduction through the neck. In this topic we will see the effectiveness of CFD tool for modelling neck of dewar. In this case we have taken the neck of main dewar which was fabricated in Vacuum Techniques Private Limited.

At first we have used the theory available with us and calculated the load coming through the neck when the cryogen reservoir is filled up to the brim by varying the mass flow rate of the evaporating fluid and then the Ansys Fluent software to predict the load coming to the dewar.

Case

We have a cylindrical neck of OD 114.3 mm, thickness 2.1 mm and length 320 mm. The theory produced by R.B.Scott and R.R.Conte gives the total load coming through the neck while varying mass flow rate of the evaporating fluid for fixed L/S ratio of neck.

1. Taking the relation we derived in thermal designing of neck,

$$\frac{L}{S} = (1/\dot{m}C_p)[a\Delta T + \left(K_0 - \frac{Q_1 a}{\dot{m}C_p}\right).\ln\left(\frac{Q_1 + \dot{m}C_p\Delta T}{Q_1}\right)]$$

Where, $Q_1 = \text{Conduction Heat load}$

$L = \text{Length of pipe}$

$S = \text{Cross} - \text{Sectional area of Pipe}$

$\dot{m} = \text{mass flow rate of cryogen}$

$C_p = \text{Specific Heat capacity at constant pressure}$

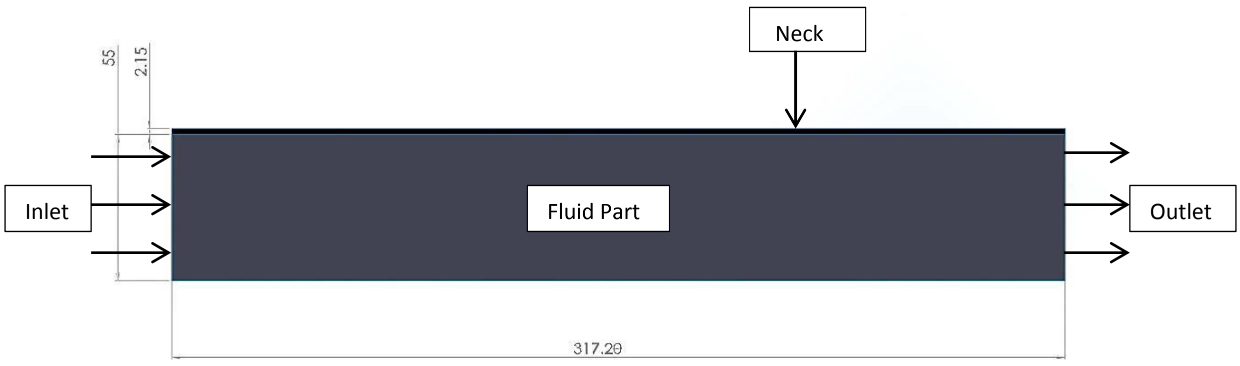
$K_0 = \text{Thermal conductivity pipe at temperature } T = T_0$

$a = \text{Constant}$, $\Delta T = T_1 - T_0$

This equation cannot be solved analytically it is an iterative process so we have used the goal seek function in MS Excel to find the solution.

2. CFD modelling of the neck with same parameters taken in the previous theory. Ansys Fluent CFD package can help us to obtain the conduction and radiation load into the dewar while varying the mass flow rate of evaporating fluid.
   (I) The model of neck is in axisymmetric 2D form which reduces the number of meshes while maintaining the numerical accuracy of the result.
   (II) The model of neck where a G10 pipe is added inside and concentric to the neck to increase the heat transfer between evaporating fluid and the neck.

To study the temperature profile a 2-D axisymmetric model of dewar neck with and without G10 pipe was created. Constraint temperatures were used as an input for boundary condition at dewar neck and at the fluid entrance. For outside dewar wall adiabatic conditions were assumed. Laminar model was used to model the flow.



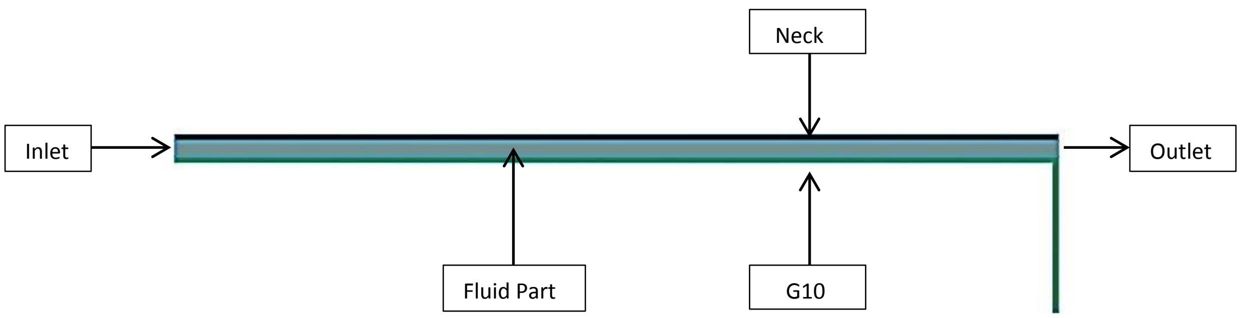


Fig.7.10 2-D axisymmetric model of dewar neck with and without G10 pipe for CFD analysis

	Fluent (Neck)		Fluent (Neck with G10)		Conte Theory	
$\dot{m}$ ($\frac{kg}{s}$)	Q1 (W)	Q1+Qr(W)	Q1(W)	Q1+Qr(W)	Q1(W)	Q1+Qr(W)
1.00E-13	6.365272	6.365272	6.3571121	6.35711212	6.16372819	6.1637E+00
1.00E-12	6.365271	6.365271	6.3571127	6.35711293	6.15386732	6.1539E+00
1.00E-11	6.365225	6.365228	6.3571115	6.35711378	6.14519812	6.1452E+00
1.00E-10	6.365261	6.365282	6.3571001	6.35712293	6.14491256	6.1449E+00
1.00E-09	6.365142	6.365358	6.3569797	6.35720802	6.14478574	6.1450E+00
1.00E-08	6.363949	6.366115	6.3558152	6.35809843	6.14366007	6.1460E+00
1.00E-07	6.352025	6.373673	6.3441874	6.36701866	6.13228516	6.1552E+00
1.00E-06	6.23366	6.448741	6.228466	6.45673694	6.01927661	6.2485E+00
5.00E-06	5.75535	6.795527	5.7405554	6.8808681	5.53068575	6.6769E+00
1.00E-05	5.354107	7.265848	5.2019267	7.4791135	4.95204047	7.2444E+00
5.00E-05	4.30614	8.78153	2.4907209	13.5189764	1.65509185	1.3117E+01
1.00E-04	3.757266	9.582689	1.392748	21.215756	0.24753794	2.3172E+01

7.9 Comparison of the theoretical and Fluent data.

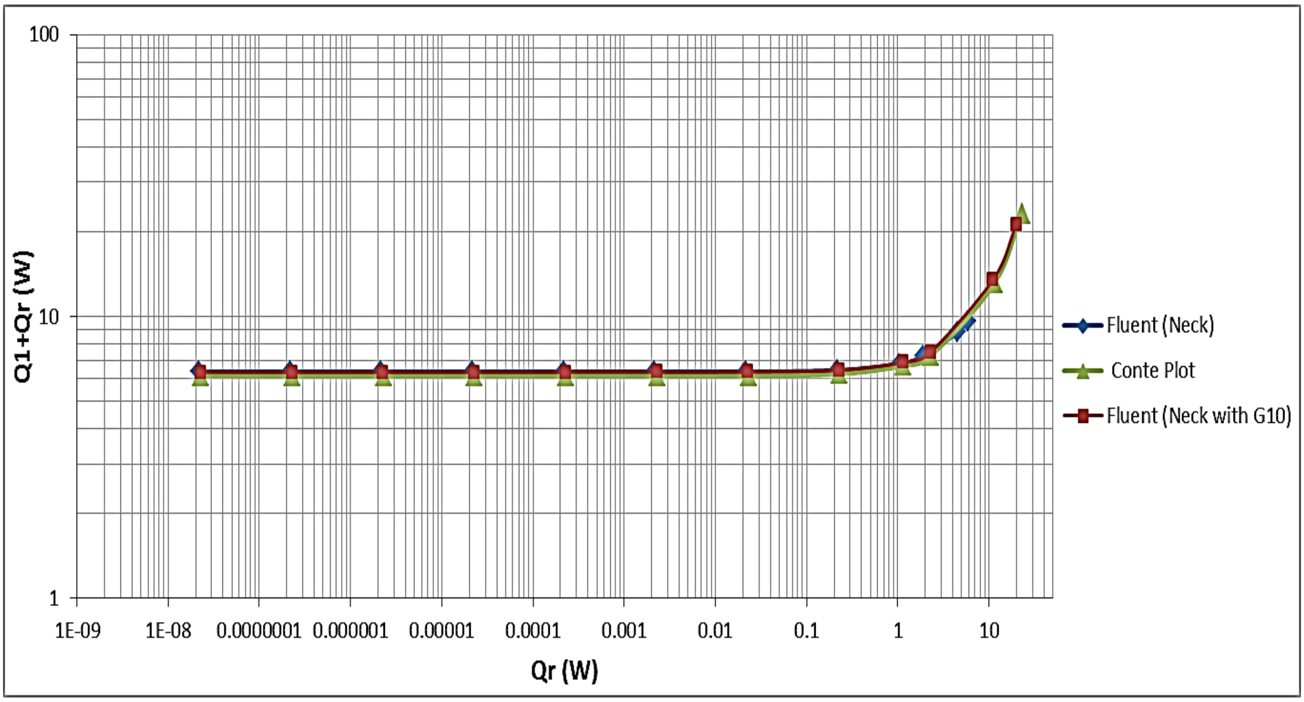
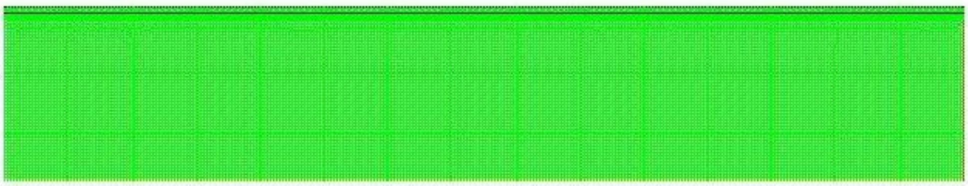


Fig.7.11 Graph for the comparison of theoretical and fluent data

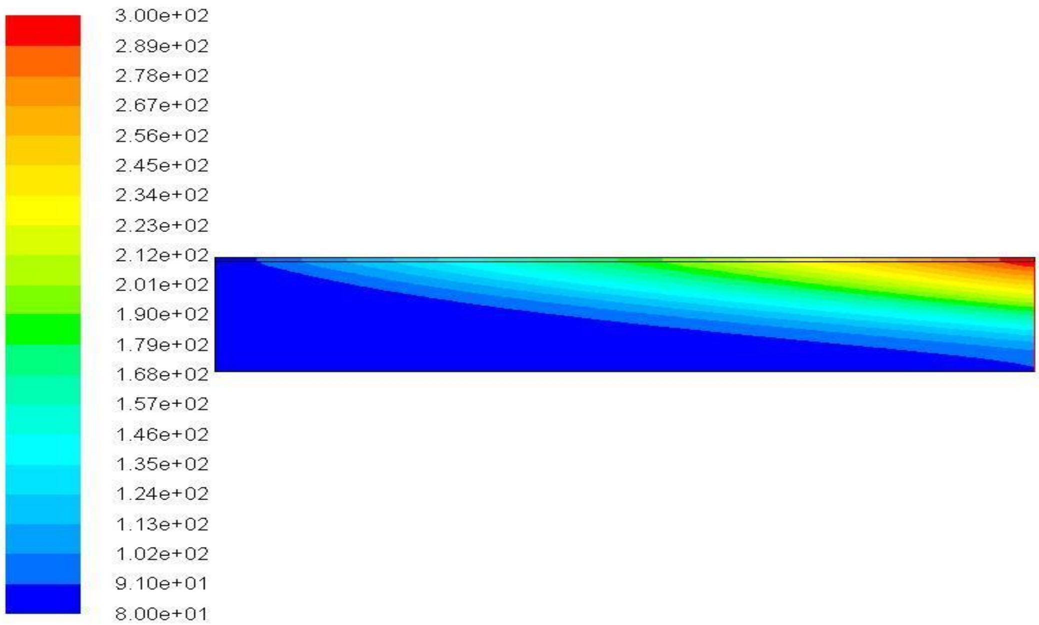
This result proves that the Ansys Fluent software is reliable, efficient and precise. We can predict the outlet temperature of evaporating fluid hence calculating realistic heat load coming in the dewar for a fixed L/S ratio of neck.

2.1 Example of fluent (Neck) simulation for $\dot{m} = 5 \times 10^{-5}\ kg/s$



Number of meshes = 21241

Orthogonal Quality of mesh = 0.75



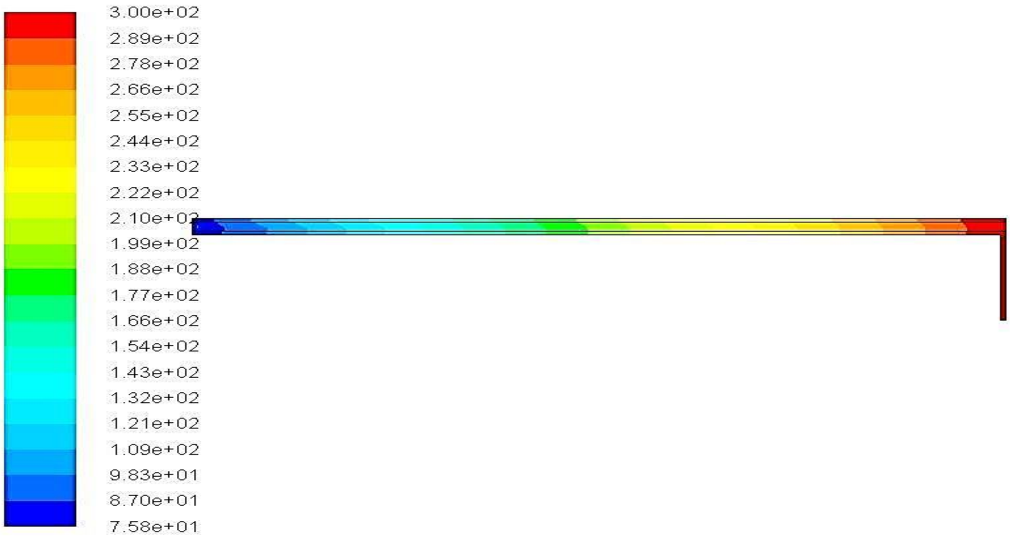

```
          Mass-Weighted Average
              Total Temperature                   (k)
-------------------------------- --------------------
                         outlet            166.55409

       Total Heat Transfer Rate                   (w)
-------------------------------- --------------------
                    bottom_wall           -4.2967882
                       top_wall            10.086329
```

Fig.7.12 Mesh, Temperature Profile and Flux report for problem 2.1

2.2 Example of Fluent (neck with G10) simulation for $\dot{m} = 1 \times 10^{-5} kg/s$

Number of Meshes = 6906

Orthogonal Quality of Mesh = 0.99



Temperature Profile of Neck with G10 pipe

```
          Mass-Weighted Average
              Total Temperature                  (k)
-------------------------------- --------------------
                         outlet            298.54504

        Total Heat Transfer Rate                 (w)
-------------------------------- --------------------
                    ss_bottom_wll           -5.2019267
                      ss_top_temp            7.5172086
                ---------------- --------------------
                            Net             2.315282
```

Fig.7.13 Mesh, Temperature Profile and Flux report for problem 2.2

As we can observe that the results obtain by the theoretical method and CFD method where a G10 pipe is used to increase the heat transfer between neck and evaporating fluid are almost same. The reason being the temperature difference ΔT which is constant i.e. 220 K for the theoretical method and with G10 pipe inside the neck the outlet temperature of fluid is almost same as the atmospheric condition.

7.3.2 VAPOUR PRECOOLING WITH REGENERATOR

We have tried to numerically model the best case where N_2 flows through the neck of the dewar. There is no theoretical way to predict the exit temperature of the N_2 gas and how the regenerator cools the gas we have used Ansys Fluent CFD package to determine the temperature within the dewar neck.

There are some limitations with CFD modelling for this case as internal dynamics of helium inside cold head and the movement of pneumatic displacer where regenerator is housed is unknown to us in this simulation, hence the result tend to produce some error at predicted temperature profile and how the regenerator part of the cold head cools the N_2 gas coming through it.

From the outside the regenerator is SS casing of 102 mm in length and OD of 96 mm. At inside the regenerator is inside a G10 displacer with a gap of few microns between the SS wall and displacer. This gap of few microns is filled by the working gas in this case Helium.

To study the temperature profile a 2-D axisymmetric model of cryocooler cold head with dewar neck was created. Constraint temperatures were used as an input for boundary condition along the cold head and at the fluid entrance. For outside dewar wall adiabatic conditions were assumed. Compressible flow was modelled using transition SST model for a constant mass flow rate.

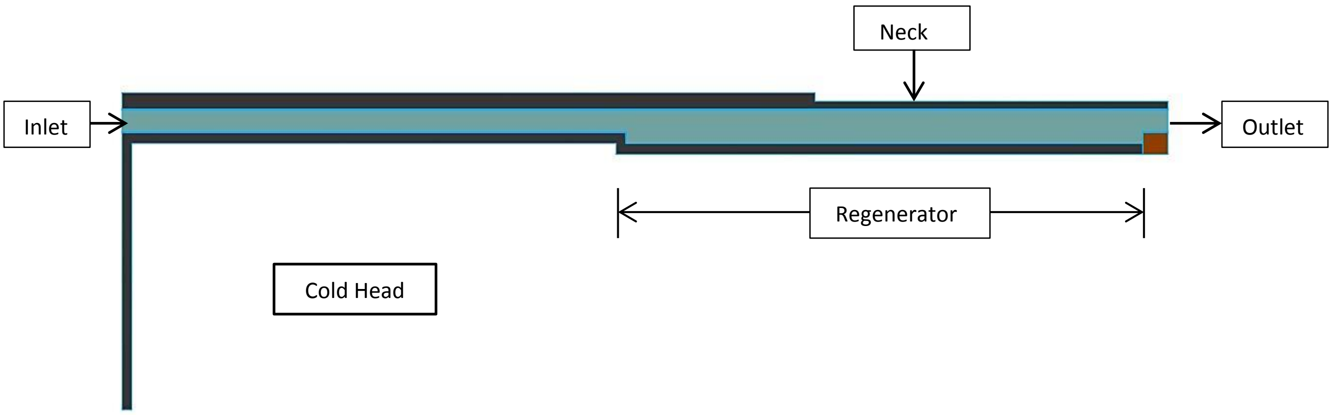


Fig.7.14 2-D axisymmetric model of cold head with dewar neck for CFD analysis

Number of meshes = 18073 Orthogonal Quality = 0.99

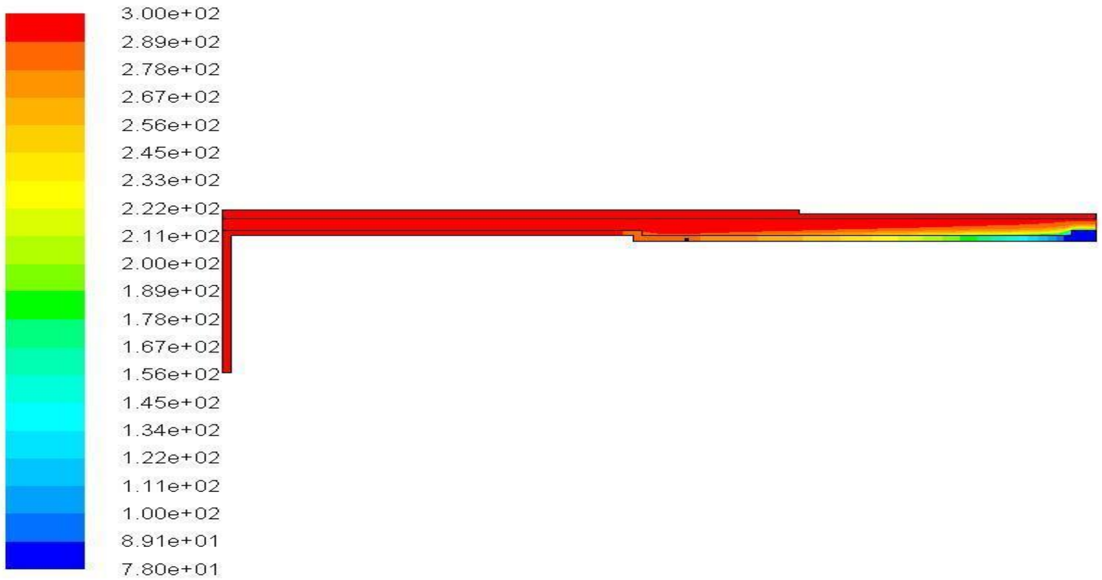


Fig.7.15 Mesh and Temperature Profile of the fluid through the regenerator

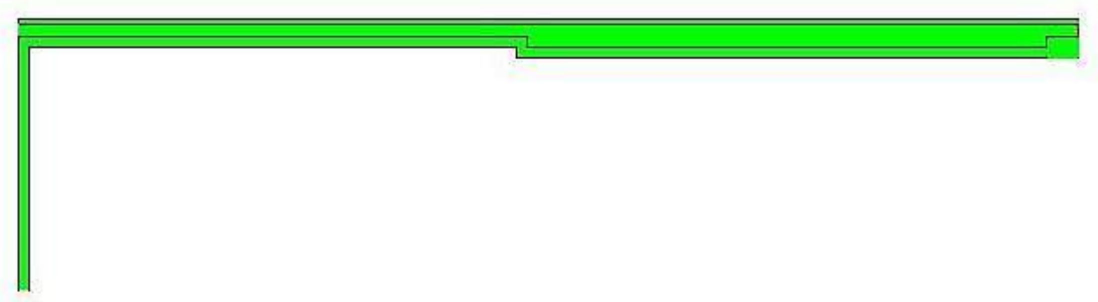
This 2-D simulation was done with a mass flow rate of 0.68 g/s that gave us the temperature of fluid at exit of regenerator as 256 K. The result at steady state conditions shows that there is some amount of precooling by the regenerator part of the cold head and it also doesn't affect the performance of the cryocooler as we have seen with experimental data.

If we take the inlet temperature of nitrogen gas as 300 K the temperature obtained in this simulation is lower than the expected which would be around 270 K. Considering the refrigeration capacity given by the manufacturer as 266 W at 80 K there is an error of 7% in the result obtained with fluent than the experimental data.

Let us reduce the gap between the cold head and the pipe by reducing the OD and ID of the pipe with same length. As we know if the cross sectional area of annular space is reduced turbulence will increase and hence heat transfer between the regenerator and the fluid will increase. The other advantage is cross sectional area of neck will decrease for the same length which will reduce the conduction load coming on the cryogen reservoir, since it cannot be done practically in this setup we have tried to model it in Ansys fluent CFD software.

Example:

Neck with cold head with 2.5 mm annular gap.



Number of Meshes = 49580

Orthogonal Quality = 0.96

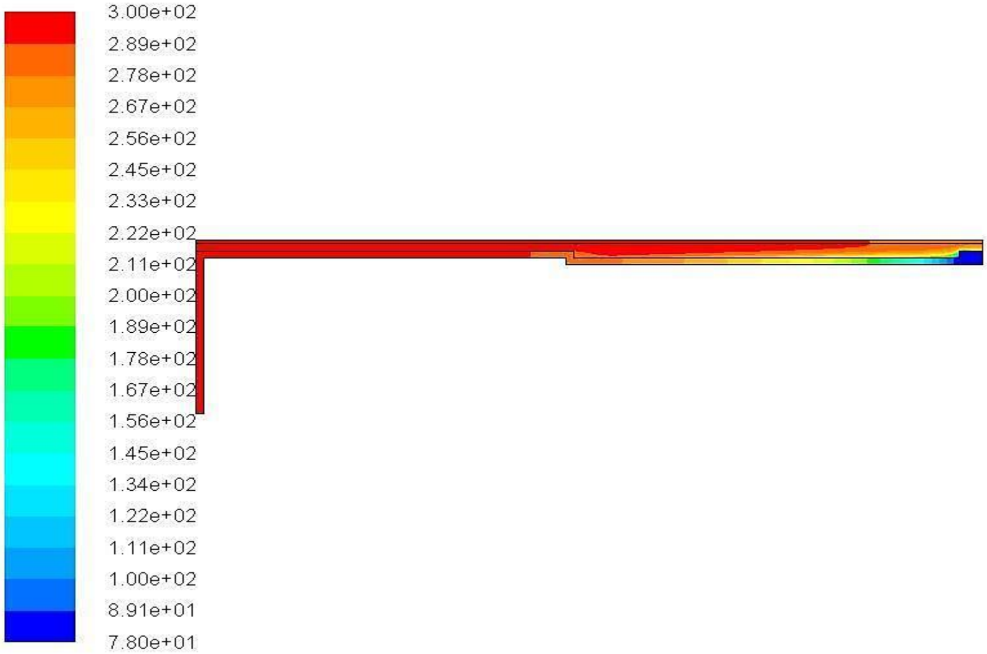


Fig.7.15 Mesh and Temperature Profile of the fluid through the regenerator for reduced annular gap.

The outlet temperature here was reduced to 247 K from the previous case where it was 256K. This means that by reducing the annular cross sectional area between them the temperature and the precooling effect by regenerator can be enhanced which transpires in increase in production rate of liquid Nitrogen.

If the annular gap is reduced to 1 mm the temperature goes down to 235 K, hence from this simulation and our theoretical data we can infer that the annular gap must kept to a minimum as possible to enhance the use of regenerator part of cold head. This also has an advantage of reducing the conduction load coming through the neck of dewar.

Annular Gap (in mm)	$\dot{m}$ ($\frac{kg}{s}$)	Nitrogen Inlet Temperature (K)	Nitrogen Exit Temperature (K)	Enthalpy Removed (J/kg)
4.1	6.8E-4	300	256	45
2.5	6.8E-4	300	247	55
1	6.8E-4	300	235	68

7.10 Summarised data of the Ansys fluent simulation of regenerator precooling

CHAPTER 8

8. CONCLUSION

- An experimental dewar of 28 Litres capacity was designed and developed with two inlet port to test the cryocooler and for liquid nitrogen production in IUAC, New Delhi and a main dewar of 250 Ltr capacity for commercial purpose fabricated by Vacuum Techniques Pvt. Ltd.
- Eight silicone diode temperature sensors were calibrated from 60 K to 300 K and were placed in specific position in experimental dewar and on cold head to gather data for theoretical and analytical study of the setup.
- Experimental runs with different scenarios were done to optimize the production rate of the setup.
- CFD modelling to study the effect of regenerator on liquid nitrogen production and vapour precooling effect of nitrogen gas to reduce the conduction load through neck of dewar.
- Maximum production rate of 74 Ltr/ day was achieved in the experimental setup and 64 Ltr/day in the main setup.

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