DEVELOPMENT OF CCR BASED VARIABLE TEMPERATURE INSERT FOR CRYOGEN FREE SUPERCONDUCTING MAGNET SYSTEM

Thesis submitted in partial fulfillment of the requirements for the Degree of

Master of Technology (M. Tech.)

In

MECHANICAL ENGINEERING
(Specialization: Cryogenics & Vacuum Technology)

By

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Certificate of Approval

This is to certify that the abstract entitled "**DEVELOPMENT OF CCR BASED VARIABLE TEMPERATURE INSERT FOR CRYOGEN FREE SUPERCONDUCTING MAGNET SYSTEM",** being submitted by **Mr. Mukesh Dhakarwal**, Roll No. 212ME5325 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.

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CONTENTS

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ABSTRACT

Cryogen free magnet systems using close cycle refrigerator(CCR) is gaining more attention nowadays with continuously increase in advancement of performance and reliability of the close cycle refrigerator. In research lab and institutes, material characterisation is done which includes study for basic material science. As it is evident that sample properties depend on the sample space temperature, which require variation of magnetic field with variable sample temperature. Hence, the need for variable temperature insert for cryogen free magnet system came into existence. This thesis reports the design and fabrication of variable temperature insert for cryogen free magnet system with temperature variation from 4.2K to 300K and sample space of 25mm. The experimental set up comprises of GM cryocooler, vacuum jacket, thermal shield, heat exchangers, charcoal adsorber, sample bore and sample holder, buffer tank, scroll pump for circulation of gas. It also includes the manufacturing of three conduction-cooled (Helical coil) heat exchangers(HX) by using copper tube which are cooled with the help of the CCR. In this experimental set up, Thermal shield is connected with 1st stage of the CCR and maintained at temperature of 1st stage of the CCR i.e. at 30 K whereas two heat exchangers are connected on 1st and 2nd stage of cryocooler.

The objective of this work is to develop a system to cool sample space from 300 K to 4.2 K. It can be achieved by the circulation of helium gas. The helium gas is cooled by the HX ,cooled by the CCR. It takes 15 hrs cool the helium gas to the desired temperature. Multiple test runs are done to test the stability of the system under fine controlled flow rate and system is working extremely well, Variable temperature insert(VTI) is successfully integrated with the cryogen free magnet system and experiment with variable temperature and varying magnetic field can be performed as the system is in fully working state.

LIST OF FIGURE

CHAPTER 1

INTRODUCTION

1 INTRODUCTION

The development in field of superconducting magnet system increases the demand for materials which are used to make superconducting magnets which ranges from LTS, MTS, HTS wire. But the major problem concerned with them is the temperature required for these materials. Hence, NbTi and Nb_3Sn are considered as most easy and convenient material to make superconducting magnets. But major problem concerned to use these materials is that of their critical temperature i.e. below 20 K so helium is required to attain this temperature. Earlier in 1990s magnets are immersed in liquid helium which result in the magnet temperature 4.2K or below and since magnet is dipped in liquid helium there will be large heat transfer. As helium is on the edge of extinct, the demand for the cryocooler increased to achieve this temperature. With continuously application of cryocooler in the superconducting magnet field which led to introduction of cryogen free superconducting magnet systems. These systems are based conduction, which is cooled by direct contact with the cryocooler or by using some extended surface, which cools the magnet. With the recent development of refrigerators and cryogen free system had significantly reduced or we can say eliminated the need of liquid helium

High magnetic field and low temperature plays an important role in the research field. Variable magnetic field and variable temperature environment at the sample space help in characterization of different properties of the materials. So there is requirement for the variable temperature insert.

The experimental set up comprises of cryogen free magnet and variable temperature insert (VTI) which is cooled by using cryocoolers.

1.1 BASIC PRINCIPLE OF VARIABLE TEMPERATURE INSERT

The basic principle of variable temperature insert is to cool the sample space without the use of cryogens like liquid helium or liquid nitrogen and vary the sample temperature from 4K to 300K.For cooling down the helium gas in a close loop, two stage Close cycle refrigerator (CCR) is used. Helium gas is filled in a small buffer tank from that it is circulated in a close loop through a dry vacuum pump for creating a pressure difference for circulation of gas. Helium gas before putting in the sample space it passes through a charcoal adsorber and three heat exchangers. As the gas enters into charcoal adsorber which is connected to the first stage, impurities like nitrogen, oxygen and moisture get trapped inside the charcoal. Then the gas enters into 1^{st} HX that cool the gas from 300K to 30-40K. The 30K gas is passed through the 2^{nd} HX and get cooled to 4-4.2K. The 4K gas then feed to the sample space and cools the sample.

1.2 OBJECTIVE OF STUDY

At present scenario, helium is used at various labs where properties and characterization of materials is done. To setup a liquefaction facility in small labs and research institutes is a costly issue and maintenance of liquefaction system is a major issue. With the development of CCR's dependence on liquid helium is drastically reduced. After the successful development of cryogen free magnet system(CFMS), development of variable sample temperature for the cryogen free system without using liquid helium is a major challenge and to make a fully indigenous CFMS that can compete with the commercially available system so that cost of the CFMS get reduced and research at low cost can be done. The objective of the work is as follows:-

i) Testing and commissioning of variable temperature insert for CFMS without use of liquid helium by conduction cooled gas using CCR.

ii) Proper documentation for future study on variable temperature insert.

iii) To obtain a sample temperature in the range of 4K-300K using conduction cooled gas by CCR.

1.3 PRINCIPLE COMPONENTS OF VTI

Components of VTI are:-

1. Cryocooler
2. Vacuum Jacket
3. Thermal Shield
4. Heat Exchangers
5. Charcoal adsorber
6. Sample holder
7. Buffer tank
8. Scroll pump
9. Relief valve

CHAPTER 2

LITERATURE REVIEW

2. LITRATURE REVIEW

According to research of different organization showing the statistics of helium reserves on earth shows an alarming situation. The cost of liquid helium in the last five years in UK was hiked by almost double and is still going high. However, in future, we may face a much more serious problem. According to the Helium Privatisation Act (1996) the US Federal Helium Reserve could be sold by 2015 which is creating a fear in the low temperature community that the situation with recent gigantic ^{3}He cost jumps may repeat itself with ^{4}He. There is also very strong environmental aspect of this problem. According to William Halperin: "Helium gas is a natural resource which is not replaceable and when released it will rise through, and escape from our atmosphere and be gone forever."[11]

According of ISIS statistics 25-30% percent of the experiment require cryogenic temperature at the sample space.[11]

2.1 IDEA BEHIND VARIABLE TEMPERATURE INSERT

With the increasing number of superconducting magnets in the research labs and institute where characterization of material properties need of liquid helium is increasing day by day and helium reserves are limited. Cryogen free superconducting magnet system came into existence which drastically reduced the consumption of liquid helium. As the commercial companies are making these CFMS with variable sample space temperature. Importing these system costs huge, maintenance and servicing is also a issue, so by keeping in mind IUAC New Delhi had successfully developed CFMS with room temperature sample bore. So to develop a system which is capable of competing the existing commercial product, sample space temperature need to be varied from 4K to 300K.But major challenge is that due to propriety issue behind the concept of the commercial product, designs are not disclosed. With all these issue in mind we had started this project, to make a system that can very sample temperature from 4K to 300K.

2.2 HISTORY OF MAGNET AND VARIABLE SAMPLE SPACE TECHNIQUES

The helium gas was first liquefied in 1908 by Kammerling Onnes. In 1911,he discovered the phenomenon of superconductivity in Mercury. These two discoveries had revolutionized the research in the field of magnets and materials

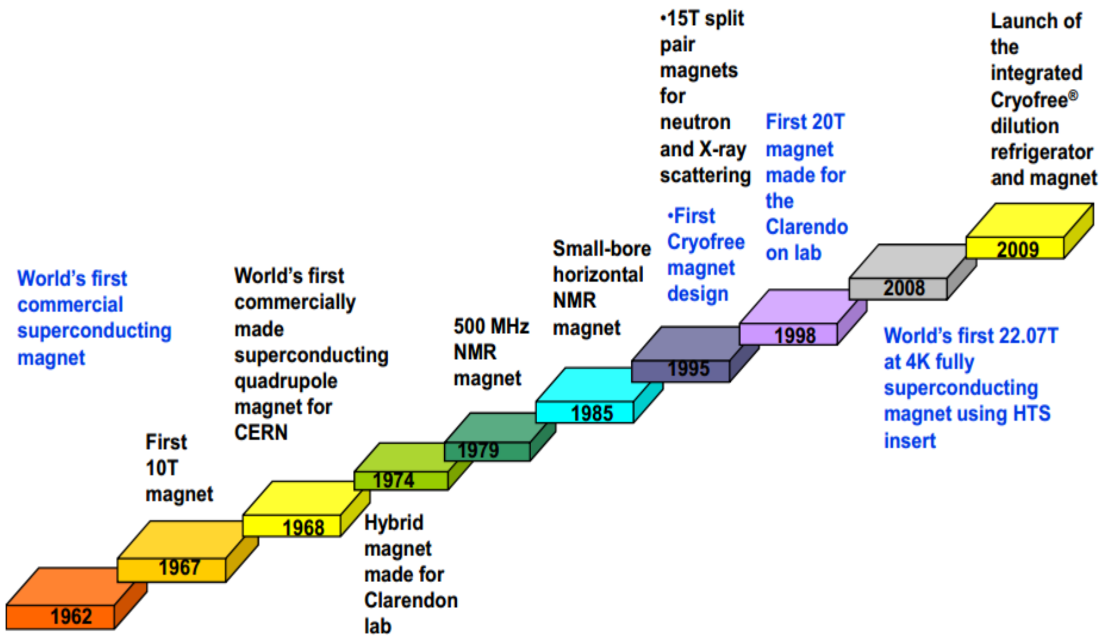

Figure 1: Development in the field of superconducting magnet. [source: Oxford Instruments]

Chandratilleke et al. (1996) developed heat switch for precooling, is used in superconducting magnets, which are cooled by two-stage GM cryocoolers. The study is focused on shortening of cool down time of cryocooler-cooled 6T and 10T superconducting magnets. The study also shows that in the temperature range 70 to 300 K, the switch provides a 80 W refrigeration capacity at the 2nd refrigeration stage, which is about four times higher capacity than the 2nd stage alone can provide at that temperature range[12].

Urata et al. (1996) developed a 10T cryo-cooled NbTi/Nb3Sn superconducting magnet with 100 mm room temperature bore. The study is concerned on the development of 4K GM refrigerator, using Er_3Ni regenerator material, cooled the magnet without help of liquid helium. The study also shows the use of Bi(2212) current leads to reduce heat leakage into the on 2^{nd} stage of refrigerator.

Demikhov, E et al. (2010) developed and tested a conduction cooled 8T superconducting magnet system with variable temperature insert. The development shows that the sample space temperature varies from 5.5-300K using helium gas, which is filled in the sample space at low pressure. In this development, a heat switch is also used in thermal coupling between sample space and the 2^{nd} stage of CCR[19].

Choi et al.(2010) developed a CCR cooled NbTi superconducting magnet. A NbTi magnet of 52mm room temperature bore is developed. The study is down on the process of design, fabrication and charging test. This study is also concerned about the performance of the conduction cooled superconducting magnet system with respect to supplied current and contact resistance[18].

CHAPTER 3

EXPERIMENTAL TEST SETUP

3. EXPERIMENTAL TEST SETUP

Figure 2: Experimental Test Setup

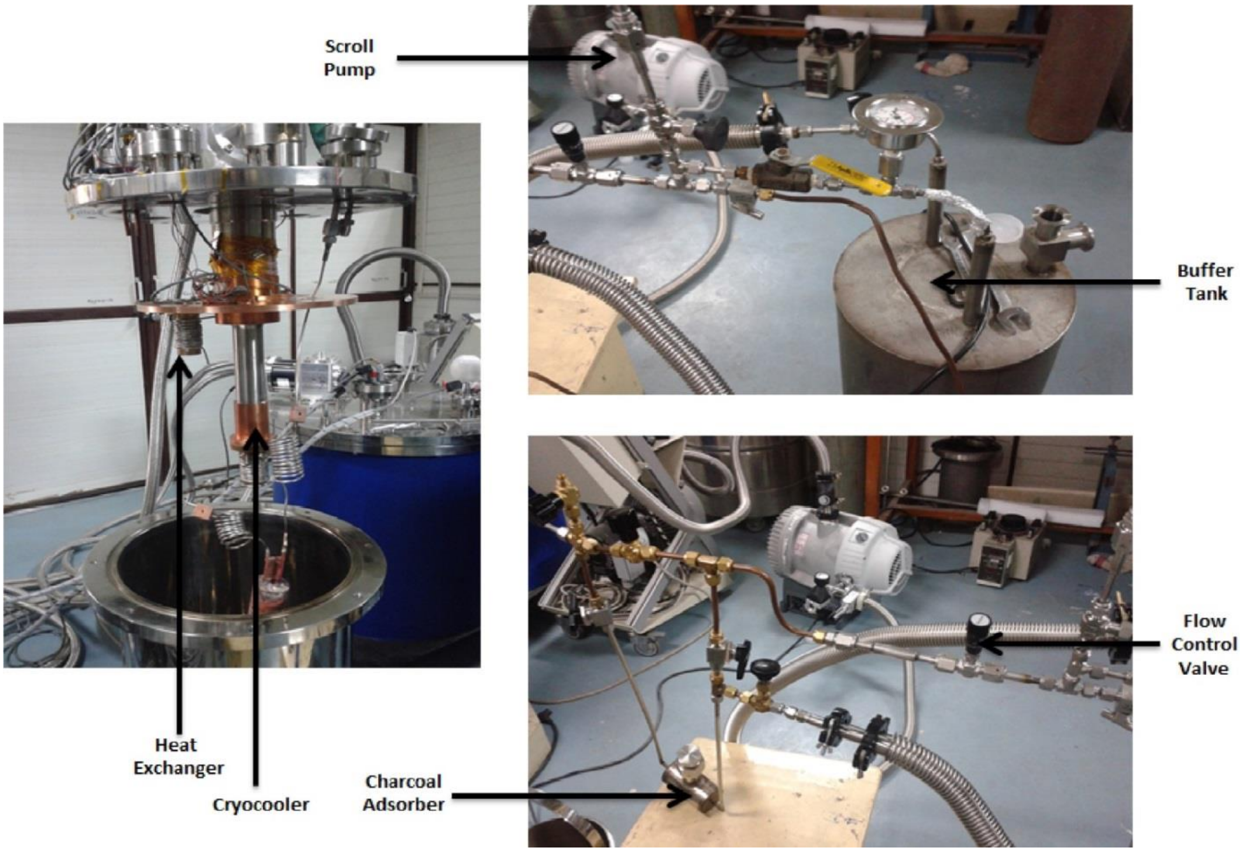

Figure 3: Complete assembly of experimental test setup

To design the VTI system a experimental test setup was developed and testing is done on a existing CCR based small cryostat.

In designing of variable temperature insert heat exchanger design and heat load minimization are two crucial things for the successful development of the VTI system

Heat Exchangers

Heat exchangers are fabricated at the workshop of IUAC. Initially in test setup the 1/8" SS tube is brazed with the brass block which is to be attached on the 1st stage and 2nd stage of the Close Cycle Refrigerator. Most important parameter for good results is proper brazing of the SS Tube with the brass block as the gas flowing in the tube is cooled by conduction from the brass block to the tube and brass block is cooled by CCR[20].

Brazing is done using woods metal[27] which is a good conductor but not as good as silver which is also used in brazing but sliver brazing is not possible in lab that's why woods metal is used for brazing. Melting point of woods metal is little bit above boiling temperature of water[27], due to which is easy to use this metal for brazing in laboratory environment where high temperature facility is not available. But is not the most favourable for brazing in commercial scale, silver brazing is best preferred. All connections are made in the workshop of IUAC including Buffer Tank, charcoal adsorber, and interconnections of the line for circulation of helium in a close cycle.

Success of any design and development lies in proper analysis and research and testing of components locally before going for fabrication stage

Successful development of any idea require many stages of development at local level prior to the final development. In the same way we had fabricated all the components before finalizing the design and sending for fabrication to vendors that fabricated the components.

Heat Exchangers are fabricated locally at workshop of IUAC. In our final design we had fabricated heat exchangers using copper tube but in experimental setup we are using SS tube which is brazed with the brass block.

Experimental setup consist of two heat exchangers one at 1st stage of the CCR which is maintained at 30K, and other heat exchanger is bolted on the 2nd stage of the CCR which is supposed to be at 4K.

3.1 PROCEDURE

The basic procedure of the experimental test setup

Helium gas which is maintained at 15 psi in the buffer tank passed through charcoal bed which is dipped into the small liquid nitrogen bath to adsorb impurity present in the gas as little bit presence of impurity (N2,H2O) in the system may result in blockage of whole system as working temperature is below 10K due to which nitrogen present in the tank will freeze in line. As the helium gas passes through there will be pressure drop which is observed in the pressure gauge connected between charcoal bed and 1st heat exchanger at the inlet of the test cryostat .After purification of the gas, it enters to the 1st heat exchanger which is mounted on the thermal shield connected to the 1st stage of the CCR. At this stage, 300K helium gas gradually cools down to 30-40K. This 30-40K gas is the deciding factor of the outlet temperature of gas coming out of 2nd heat exchanger, because this will give load to the 2nd stage of cryocooler which is having limited capacity of 0.8W at 4.2K. If the inlet temperature is 40 K then to achieve 4.2 K at 2nd stage is not possible.

Helium gas coming out of 1st heat exchanger is feed to the 2nd heat exchanger which cools the gas to 4.2 K and then it is used to cool the sample space and after cooling the sample gas is again pumped to buffer tank. This cycle continues till the experiment is performed. Temperature of each stage is monitored using silicon diode sensor(DT470, Lakeshore Cryotronics) that are mounted on copper blocks brazed on the SS tube at different sections of the whole length of tube. Heater is used to rise the temperature of the sample, heater is put on the sample holder which is a small can in experimental setup, not the actual sample holder.

Flow rate is major issue in getting 4.2 K temperature as increase in flow rate will increase load on 1st and 2nd stage of CCR so to control and monitor the flow rate a fine control valve is used at the outlet of the buffer tank and after valve a flow meter is connected to monitor the flow rate.

3.2 EXPERIMENTAL TEST HEAT EXCHANGER

Figure 4 : Test Heat Exchanger

Heat Exchangers are one of the most important components of variable temperature insert. These heat exchangers are not the common heat exchangers that are used in may system. Since the system is cryogen free all the cooling is through conduction, SS tube is brazed on the brass block which is to be mounted on 1st and 2nd stage of the CCR

Helical tube heat exchanger cooled by CCR are fabricated for the variable temperature insert system.

SS Tube is brazed on a brass block so that when the brass block temperature goes down it will cool down the gas.

A typical helical tube heat exchanger is designed having a small cylindrical brass mass attached to the CCR, a helical SS tube is wound, and brazing is done on the external surface of the brass mass. Different length of tube for 1st and 2nd stage heat exchangers are fabricated and tested using GM cryocooler to cool the gas from 300 K to 4K. Experimental analysis of both heat exchangers is done to validate the design parameters of the brass block and length of the heat exchanger tube[20].

Heat exchanger is made by brass block of 72 mm length and 60 mm diameter and brazed with 1.4m length 1/8" SS tube. Helical coil heat exchanger is designed to cool the helium gas from 300K to 4K using CCR. Heat exchangers are designed keeping in mind the optimized length of the SS tube and to achieve 30 K temperature at the 1st stage of the CCR due the limitation of surface are of the close cycle refrigerator (CCR) cold head and minimizing load on the 2nd stage of the CCR.

3.3 EXPERIMENTAL PROCEDURE

This section illustrates about the experimental test setup, procedure and testing of the test setup of VTI. Variable temperature insert works on the conduction cooling of helium for cooling the sample space of the cryogen free superconducting magnet system, so before fabrication of the main system different parameters are tested and validation of the design parameters a test setup is made using existing cryostat.

3.4 OPERATION OF VTI SYSTEM

The operation of the experimental setup of VTI system was conducted for several sessions and for cooling the helium gas heat exchangers are used to cool down the gas by conduction through CCR cold head.

The operation of experimental test setup undergoes the following:-

1) Purification of helium gas
2) Cool down of circulating helium gas
3) Sample cooling and temperature variation

Purification of Helium Gas

In VTI system purity of helium is major concern for successful run of test system, to remove the nitrogen content in the helium charcoal adsorber dipped in liquid nitrogen to adsorb the nitrogen content, which is connected at the outlet of the buffer tank. As a small amount of nitrogen content may result in chocking of line at 2nd heat exchanger

Cool down of circulating helium gas

In cool down process, the helium gas after purification from charcoal adsorber is supplied to inlet of the 1st heat exchanger connected at the 1st stage of the CCR. From the outlet of the 1st heat exchanger the gas is released at temperature between 30K to 40K and deliver to 2nd heat exchanger connected at the 2nd stage of the CCR. The gas once passed from the 2nd heat exchanger get cooled to temperature below 10K due to some limitation of the system which is then feed to the sample space.

Sample cooling and temperature variation

Gas from the outlet of 2^{nd} heat exchanger is feed to sample space which gradually cools down in few hours. And according to the need of the temperature variation a heater is placed on the sample holder to vary the sample temperature by giving power to heater and sensor is mounted to monitor the temperature of the sample holder.

3.5 RESULTS OF TEST SETUP

TEST RUN 1

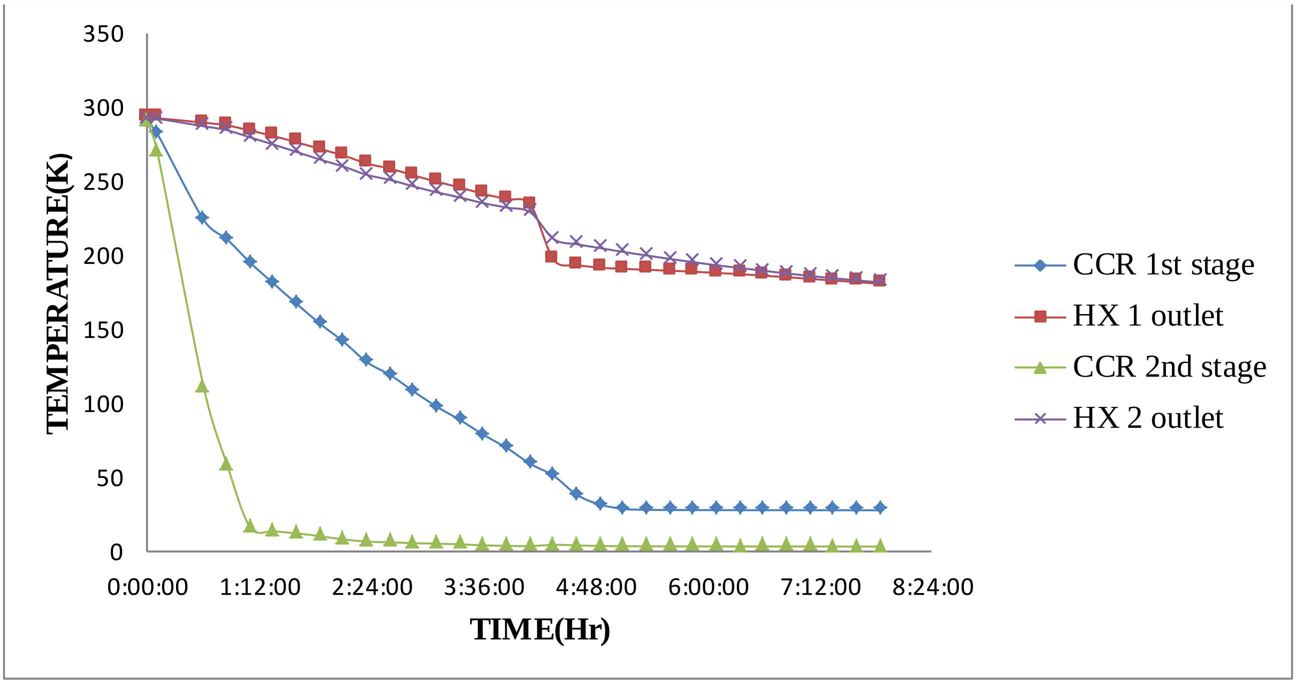

Figure 5: Test Run 1

Operating Pressure	15psi
Flow Rate	No control valve
Charcoal adsorber	No purification is done.
Flow meter	Flow meter not used
Min. Temp. Achieved	182K
Observations	➢ Cryocooler reaches 30K 1st stage and 4.2K 2nd stage in 4hrs and achieve steady state. ➢ Circulation started after 4hr of CCR run. ➢ Fall in HX1 and HX2 outlet temperature after circulation started. ➢ After one hr of circulation the outlet temperature, get steady and no further reduction in temperature for next 3hrs. ➢ Circulation stopped after 8 hrs. of CCR run. ➢ No change in outlet pressure after the flow was stopped which indicates blockage of line. ➢ Reason of blockage may be helium used without purification.

TEST RUN 2

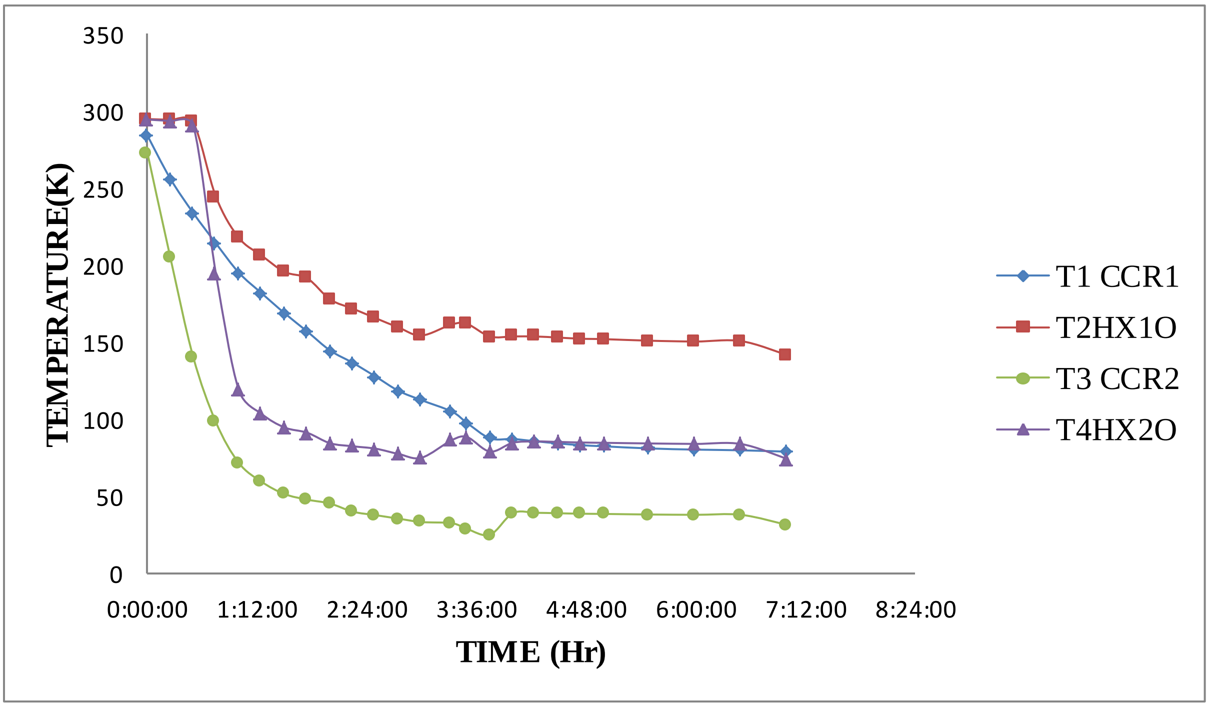

Figure 6: Test Run 2

Operating Pressure	15psi
Flow Rate	No control valve
Charcoal adsorber	No purification is done.
Flow meter	Flow meter not used
Min Temp. Achieved	74K
Observations	➢ CCR and circulation started simultaneously. ➢ Fall in HX1 and HX2 outlet temperature for 1st 3.5Hrs and then steady state is achieved ➢ Circulation stopped after 7 hrs of CCR run. ➢ No change in outlet pressure after the flow was stopped which indicates blockage of line. ➢ Reason of blockage some impurity or moisture content in the line.

TEST RUN 3

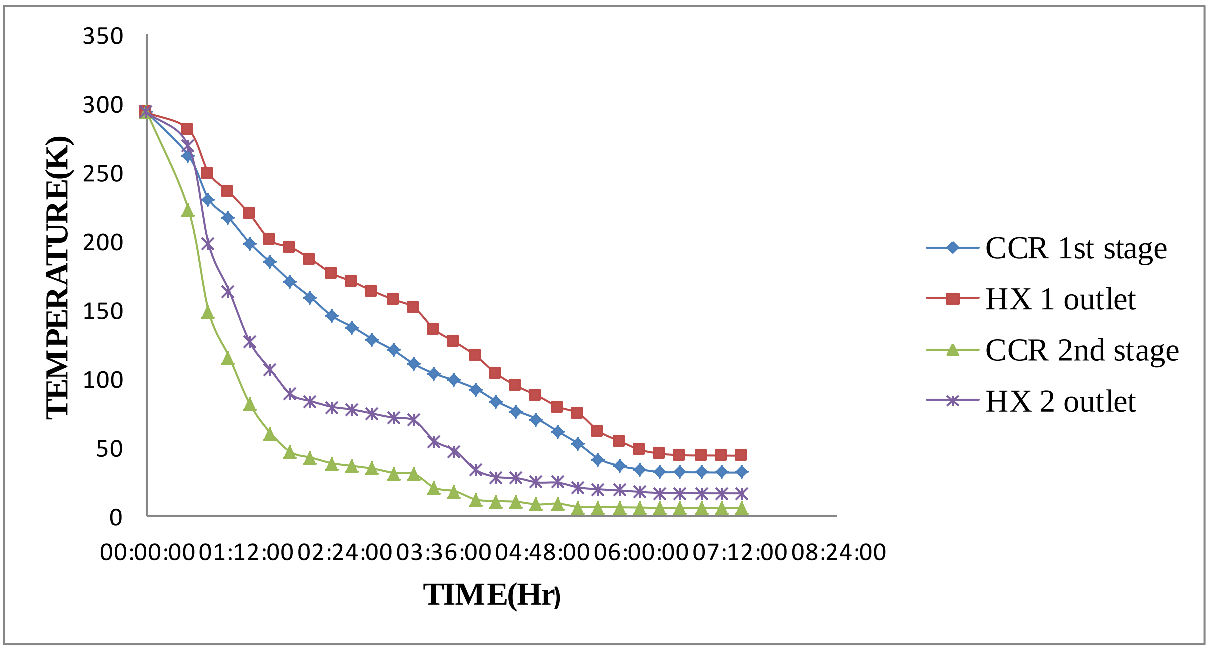

Figure 7: Test Run 3

Operating Pressure	15psi
Flow Rate	0.005g/s using fine control valve
Charcoal adsorber	Between buffer tank and cryostat inlet
Flow meter	Between buffer tank and charcoal adsorber
Min Temp Achieved	16K
Observations	➢ Cryocooler reaches 30K 1st stage and 4.2K 2nd stage in 4hrs and achieve steady state. ➢ CCR and circulation started simultaneously. ➢ Fall in HX1 and HX2 outlet temperature for 1st 6Hrs and then steady state is achieved ➢ Circulation stopped after 7 hrs of CCR run. ➢ No further reduction in the temperature. Minimum temperature of 16K achieved. ➢ Reason of temperature limitation may be contact of heat exchanger

TEST RUN 4

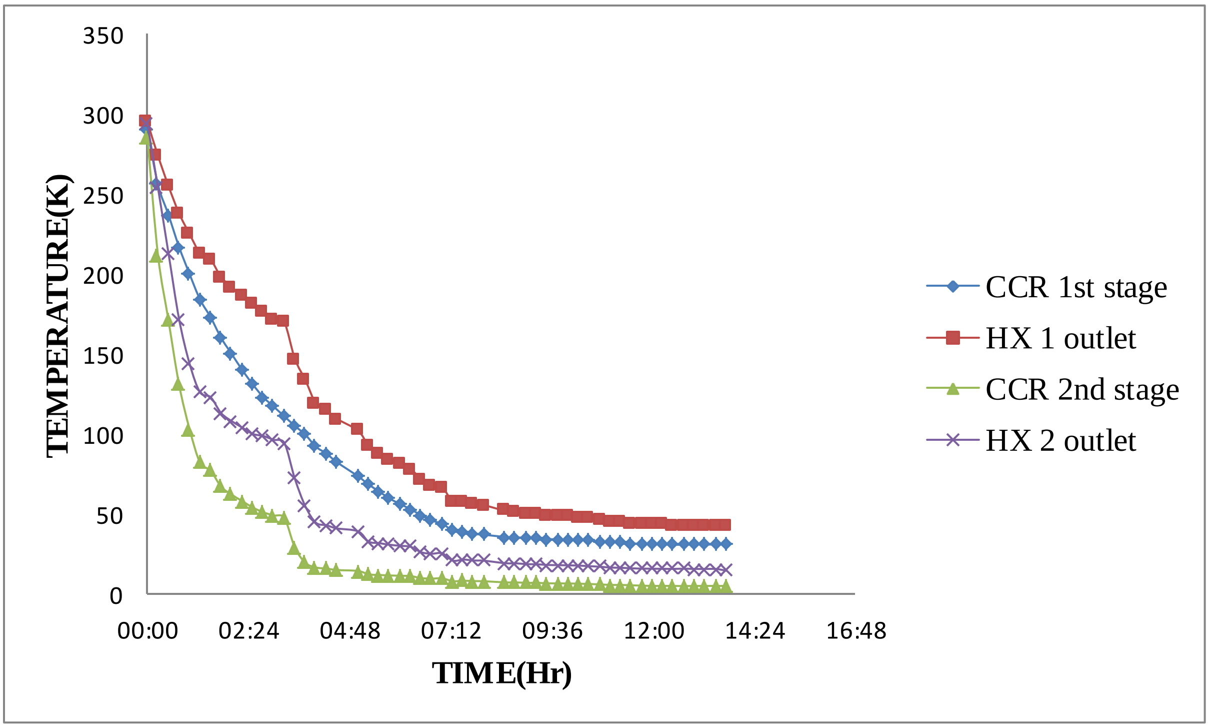

Figure 8: Test Run 4

Operating Pressure	15psi
Flow Rate	0.005g/s using fine control valve
Charcoal adsorber	Between buffer tank and cryostat inlet
Flow meter	Between buffer tank and charcoal adsorber
Min Temp achieved	14.1K
Observations	➢ CCR and circulation started simultaneously. ➢ Fall in HX1 and HX2 outlet temperature for 1st 6Hrs and then steady state is achieved ➢ Circulation stopped after 7 hrs of CCR run. ➢ No further reduction in the temperature. Minimum temperature of 16K achieved. ➢ Reason of temperature limitation may be contact of heat exchanger

3.6 LIMITATION OF TEST SETUP

As in the above graphs it is observed that the minimum attainable temperature in the test setup is 14K ,which is higher than the desired temperature.

Reasons that can be possible for this higher temperature:-

1) Brazing of SS tube with the brass block: Brazing in this type of heat exchanger is a major issue as in cooling is through conduction between brass block and SS tube, if brazing is not proper the heat transfer will not be proper and will result in bad heat transfer between brass block and SS tube. This is one of the factors that limit the outlet temperature of the two heat exchangers.
2) Brazing material: Brazing material can also be a matter for this temperature limitation as instead of silver brazing woods metal is used for brazing the brass block and SS tube, which is not as good conductor of heat as compare to silver, which is good conductor of heat.
3) SS tube as helical coil: SS tube is used instead of brass, which is excellent conductor of heat. Stainless steel tube is not a good choice for heat exchanger in CCR based heat exchangers where cooling is through conduction.so due to bad heat transfer between SS tube and brass block.
4) Temperature sensor block: Temperature sensor blocks may also a reason for such high temperature as these blocks are brazed on the SS tube in which if contact is not proper than it will show false temperature which may be 5-6 K higher than the actual gas temperature due to improper brazing and brazing material.
5) Flow rate: If all the above reasons are false then the only reason for higher temperature is the mass flow rate as higher flow rate result in increase in the heat load on the 1^{st} and 2^{nd} stage of the CCR, as cooling capacity of CCR is limited load

higher than the capacity will result in higher temperature at the outlet of 2nd heat exchanger.

3.7 REASONS FOR FAILURE OF SYSTEM

1) Blockage of line: Blockage of line is the most common reason of failure of the system. Blockage mainly occurs due to gases impurity present in helium which is circulated in closed cycle and gases impurity other than helium freezes which result in blockage of line.
2) Pressure surge: Back pressure surging result in charcoal dust in the line which gradually blocks in line when the system runs for multiple times and every time when the circulation start due to pressure surge some amount of charcoal dust enters into line.
3) Externally addition of helium: Filling of buffer tank after cool down of whole system will result in immediate blockage of line as purification of new gas is not done for multiple cycles.

CHAPTER 4

DISCRIPTION OF PRINCIPLE COMPONENTS OF VARIABLE TEMPERATURE INSERT

4. DISCRIPTION OF PRINCIPLE COMPONENTS OF VARIABLE TEMPERATURE INSERT

4.1 INTRODUCTION

Variable temperature insert plays an important role in the measurement of sample properties when the sample is placed in a magnetic field. For achieving the desired temperature range at the sample space using variable temperature insert some parameters need to be maintained in the present system.

4.1.1 TECHNICAL SPECIFICATIONS OF VTI

Flow rate	0.005g/sec
Tube dimension	ID= 2mm,OD=3.175mm
Sample space	28mm
Sample holder	20mm
Gas purity needed	99.9%
Operating pressure	15psi
Operating temperature	4.2K-300K
Absorbant	charcoal
Cooling process	CCR

4.2 COMPLETE FLOW DIAGRAM

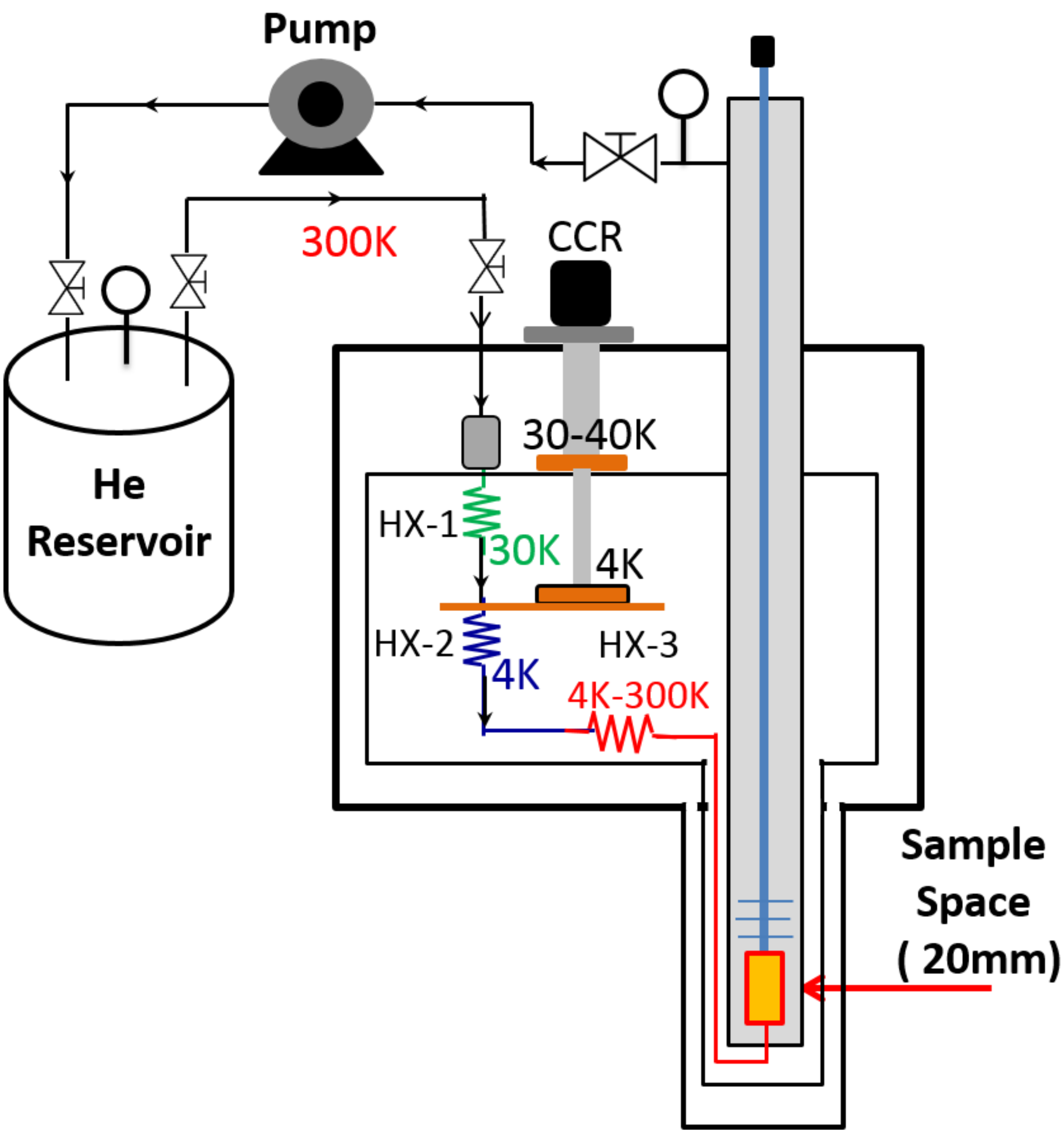

Figure 9: Block diagram of VTI system

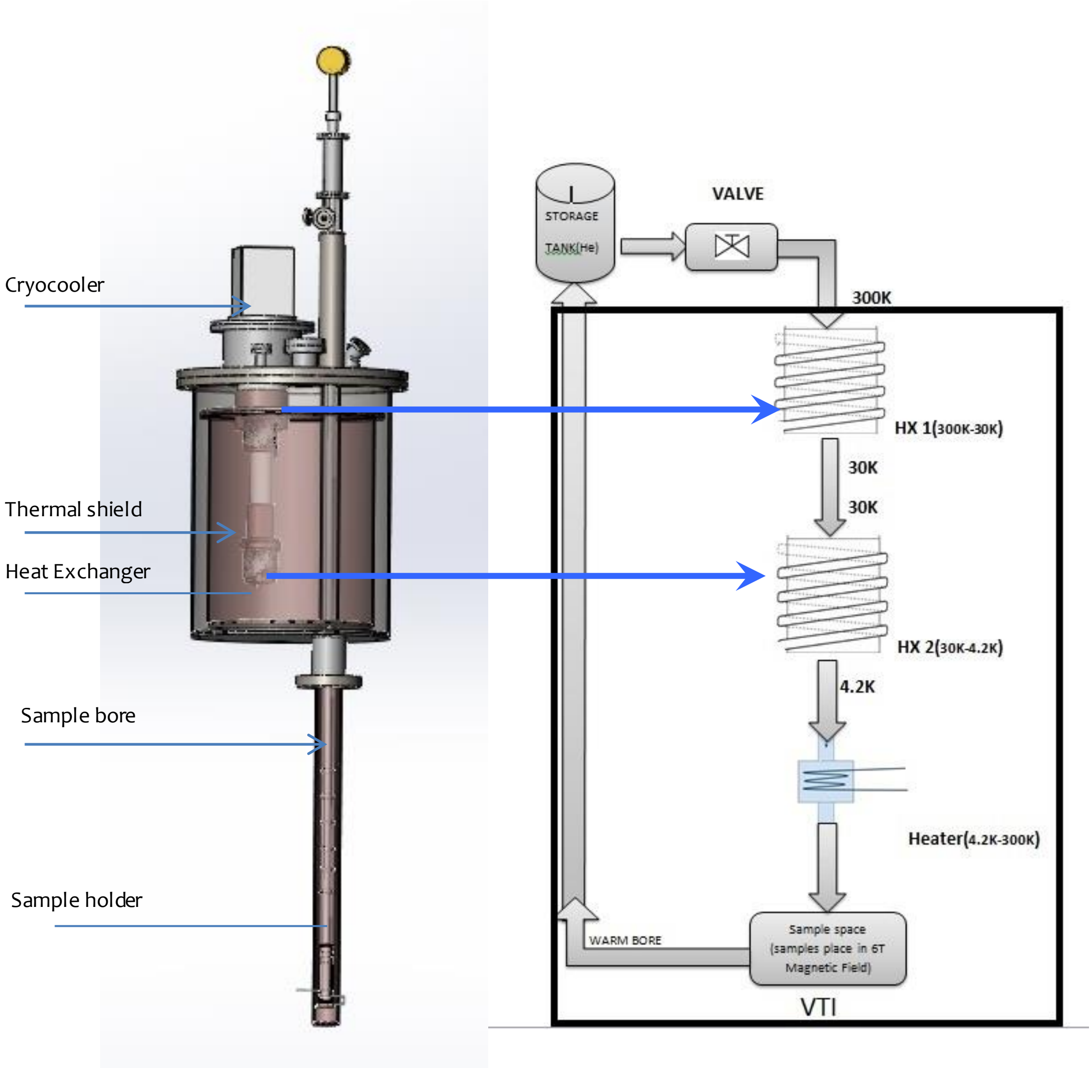

Figure 10: Solid works drawing of VTI system

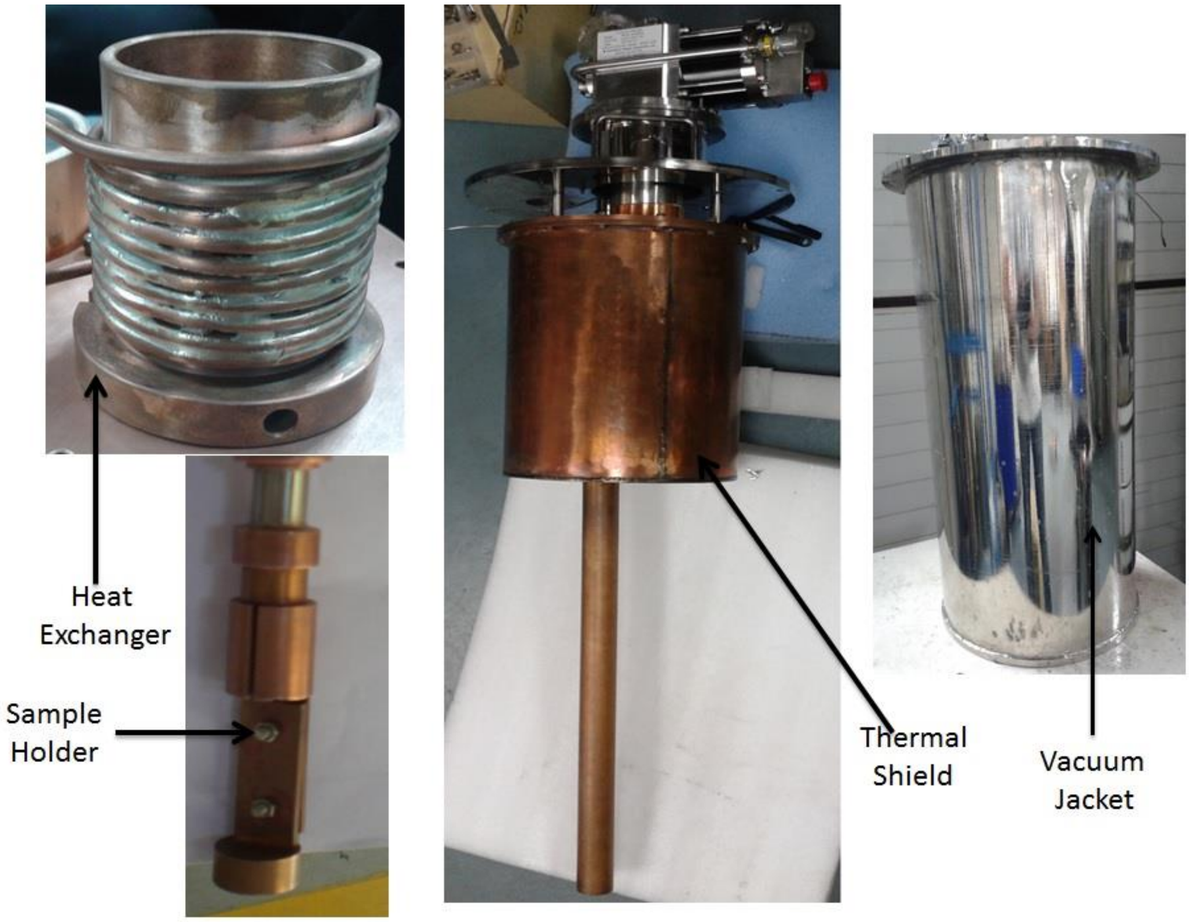

Figure 11: Components of experimental VTI system

4.2.1 BASIC PROCEDURE

Gas enters into the system from a helium buffer tank and flow rate is controlled by the valve at the inlet if the system. From the buffer tank, gas passed through charcoal chamber which is attached at the top flange of the thermal shield and the shield is attached with the 1st stage of the cryocooler which is maintained at 30K. The charcoal bed, is at 30K which ensures that all the air moisture and nitrogen will trap inside the charcoal and a highly pure gas come out of the charcoal bed. The helium gas from outlet of the charcoal bed is feed into the inlet of the 1^{st} HX which is maintained at 30K temperature so gas from room temperature or may be little bit lower than room temperature enters into the 1^{st} heat exchangers, since length of the tube is calculated and optimized for getting the desired temperature gas comes out from the outlet of the 1st HX nearly the temperature of the 1st stage of the cryocooler i.e 30K. This 30-40K gas enters into inlet of the 2nd HX which is attached at the 2nd stage of the CCR maintained at 4.2K, but this stage plays the major role in this whole system and this stage decide the desired outlet temperature is achievable or not as the refrigeration capacity of the 2nd stage of the cryocooler is limited to 1.5W @4.2 K and if load from the 1st stage is more then to achieve 4.2K at the outlet of the 2nd stage is not possible. Gas from outlet of the 2nd heat exchanger is feed to the 3rd HX which will be used for the reverse process means to increase the temperature of the gas which is coming from the outlet of the 2nd stage according to the need of the user for the experiment, one heater is mounted on the 3rd HX to rise the temperature of the gas that is to feed to the sample space from 4.2K to 300K.For monitoring the temperature of 1st and 2nd stage CCR and gas temperature at the outlet of the 1st ,2nd and 3rd heat exchangers, sensors are mounted. Now gas from outlet of the 3rd heat exchangers is feed to sample holder where sample is cooled by the gas and after cooling the sample, gas passes through the sample holder tube to the top of the tube from the top outlet scroll pump is connect that pump the gas back to the buffer tank.

4.3 DISCRIPTION OF COMPONENTS

4.3.1 GIFFORD-MCMAHON CRYOCOOLERS

4.3.1.1 INTRODUCTION

In the year 1959 W.E Gifford In the year 1959 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 up to 10 times, and the radiation load can be handled quite well by GM cryocoolers which have approx. 1.5W of refrigeration capacity at 4.2 K. This ability of GM cryocooler is used in CFMS and compact MRI systems. These are small, can be operated in any orientation, reliable, easy to construct and low cost of maintenance. GM cryocoolers are used where use of liquid nitrogen and liquid helium handling is difficult or unavailable.[8]

In this project, we have used a Sumitomo two stage cryocooler with a refrigerating capacity of 0.8W at 4.2K. Requirement of this project was to achieve a temperature of 4.2K with the limited refrigeration capacity of 0.8W.

4.3.1.2 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 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.

4.3.1.3 WORKING OF GM CRYOCOOLER

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

1) A small amount of gas enters into the cold head when the displacer is in the upper portion and inlet valve that is connected to the high-pressure (around 250 psi) helium line coming of the compressor, is in open mode.
2) After passed through the compressor and heat exchangers in the compressor the helium gas cooled down to atmospheric condition, a small volume of gas enters into the space above the displacer through high pressure line. Due to the high-pressure helium gas, 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 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.

4.3.2 VACUUM JACKET

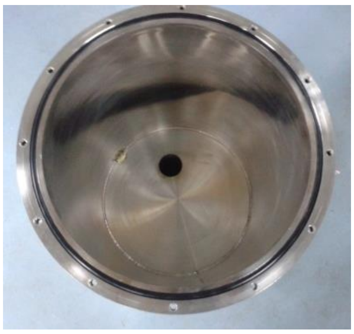

Figure 12: Vacuum Jacket

Vacuum jacket, is made of a SS304,meed to hold high vacuum in the range of 10^{-8} to 10^{-10} mbar pressure to reduce the heat load on the thermal shield maintained at 30-40K, due to the gas conduction coming from ambient.

All the components of the VTI are housed in vacuum jacket having cryocooler and Thermal shield. The vacuum jacket consist of two parts: top flange and vacuum jacket. The bolted flange seals the vacuum jacket with a viton O-ring. The internal parts of the variable temperature insert are placed in a thermal shield which is supported from the top flange of the vacuum jacket.

4.3.3 THERMAL SHIELD

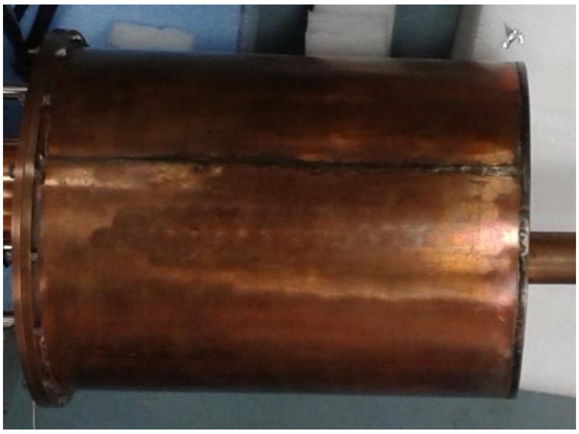

Figure 13: Thermal Shield

The thermal shield is used for reducing the radiation heat load from the atmosphere to the heat exchangers and other components of the variable temperature insert, as the system is cooled by conduction cooling from the 1^{st} stage of the cryocooler. Inserting a thermal shield in between the vacuum jacket and rest of the components drastically reduces the radiation load from the ambient to the 2nd stage of cryocooler. This shield is maintained at cryocooler cold head temperature i.e 30K.

4.3.4 CHARCOAL BED

The absorber bed is small can of copper which is connected on the top plate of the thermal shield. This bed is having coconut shell granular activated charcoal which is packed for adsorption process. At inlet and outlet steel wire mesh filter is placed to filter the charcoal dust. Charcoal is having a BET surface area of $1600m^2/gm$ this is the major reason why charcoal is most preferably used for purification of helium. As the diameter of the tube is very fine small amount of impurity can cause blockage in the line, so to purify the gas before it cooled by 1st stage of cryocooler purification of gas is a important factor which will decide the success or failure of the whole system.

4.3.5 HEAT EXCHANGER

Figure 14: Heat Exchanger

In this system three heat exchangers are used, two heat exchangers are used to reached the temperature 4.2K from 300K and one heat exchanger to increase the temperature from 4.2K to 300K. Three HXs are made by brazing copper tube on copper block which are attached on the 1st stage,2nd stage of cryocooler and 3rd heat exchanger is attached at the outlet of the 2nd heat exchanger. Heat exchangers are the major part of VTI as cooling of gas is through conduction cooling of tube and the copper block on which the coil is brazed. In helical coil heat exchangers cooled by conduction length of coil plays a major role in getting the desired temperature at the outlet

4.3.6 SAMPLE BORE

Sample bore is a long tube of stainless steel in which sample holder is inserted. It also act as a helium return path after cooling the sample holder back to the helium tank.

4.3.7 BUFFER TANK

Figure 15: Helium Buffer Tank

High purity helium gas is stored at 15 psi pressure in the buffer that which is used for cooling the sample space.

4.3.8 SAMPLE HOLDER

Figure 16: Sample Holder

Sample holder is a small copper mass used to mount the sample for testing, sensors and heater are mounted and a long hollow ½" tube is connected to this sample holder to move the sample up and down according to the way the user wants to test the sample. Bottom half part of the sample holder is removable, to reduce the sample mounting time as when one sample is testing in the meantime second sample can me mounted on the 2^{nd} removable part of the sample holder. This reduces the sample testing time.

4.3.9 RELIEF VALVE

Relief valve is a safety valve that does not allow pressure inside a system above a certain limit for which it is rated. It is designed to open at a pre-set value to protect the pressure vessel from being subjected to higher pressure than designed value.[7] In our system we have used a Swagelok 15 psi spring loaded relief valve.

4.3.10 VACUUM PUMP

In CCR based cryogenic systems there is a need to minimize the heat load from the atmosphere(300K) to the system. The maximum heat load that can transfer to the system is through convection, so to reduce convective heat load the space between the vacuum jacket and thermal shield needs to be evacuated. Turbo-molecular pump is generally used as pumping station to create vacuum in the range of 10^{-5} mbar. The heat transfer coefficient varies proportionally to pressure inside the chamber, hence higher the quality of vacuum less is the gas conduction load to the system.

We have designed an experimental setup with thermal shield and vacuum jacket. The space between vacuum jacket and thermal shield and space inside thermal shield is evacuated with help of pumping station. Vacuum inside the system is in the range of 10^{-8} mbar.

4.3.11 SCROLL PUMP

Figure 17: Scroll Pump

The XDS10 scroll pump used in this experiment for circulation of gas is a dry pump. This pump is normally used in laboratory application and used as a backing pump for turbo molecular pump. The innovative design of this pump to make completely dry pump ,bearing shield is used to segregate all types of lubricants from the vacuum environment, not only make it completely dry, but tightly sealed. . It is also used with electron microscopes and mass spectrometers.

Scroll pumps use intermeshing fixed and orbital scrolls to form non-contacting, meniscus (crescent) shaped gas pockets that are compressed continuously by the orbiting action. This means that, unlike oil-sealed rotary pumps, there is no sealant or lubricant required in the swept volume of the pump.

4.3.12 INSTRUMENTATION

4.3.12.1 Vacuum Gauge

Figure 18: Pfeiffer Vacuum Dual Gauge

A sole parameter, pressure can only measure the quality of vacuum that exist in system. So pressure measurement is an important process to measure vacuum accurately. Conventional measuring equipment like U- tube manometer, McLeod gauge are not successful in case of vacuum, since the pressure is below atmospheric pressure. So the gauges used for vacuum measurements 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.

4.3.12.2 Temperature Sensor

Silicone diode sensors are the most preferred sensor for the cryogenic application where measurements are done in zero magnetic field, mainly in the temperature range from 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 inter-changeability. 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.

The major disadvantage of silicon sensor is that they are not very accuracy, and on thermal cycling the reproducibility of these sensor is not good.

CHAPTER 5

DESIGN OF VARIABLE TEMPERATURE INSERT

5. DESIGN OF VARIABLE TEMPERATURE INSERT

5.1 THERMAL DESIGN OF VTI

5.1.1 CONDUCTION HEAT LOAD:

The heat load due to conduction that can be transferred to sample space, is through sample bore and sample holder tube as these are the only part that are directly connect to the sample space.

One dimensional heat transfer equation for conduction,

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

Here $\dot{Q} = Heat\ tansfer\ rate$ $\qquad A = Cross\ section\ area$

Since Stainless steel thermal conductivity varies with temperature, integral value of the thermal conductivity is taken. [4]

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

Heat transfer equation becomes,

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

CASE

Sample bore

We have a SS304 sample bore with ID= 28mm and OD = 32 mm and length 1500 mm. one end is at 300K and the other at 4.2K for the maximum possible heat load that can be transferred to the sample space.

For SS304 integral value of thermal conductivity from 300 to 4.2 K = 3060W/m [3]

From equation (1), total heat transferred through the sample bore

$$=3060 * 3.1416 * (.032^2 - .028^2) / (4 * 1.5)$$

$$= 0.384 \text{ W}$$

And sample holder rod

We have a SS304 sample holder tube with ID= 10mm and OD = 12 mm and length 1500 mm. one end is at 300K and the other at 4.2K for the maximum possible heat load that can be transferred to the sample space.

For SS304 integral value of thermal conductivity from 300 to 4.2 K = 3060W/m [4]

From equation (1),total heat transferred through the sample holder rod

$$=3060 * 3.1416 * (0.012^2 - 0.01^2) / (4 * 1.5)$$

$$= 0.07 \text{ W} \sim 70 \text{mW}$$

REDUCTION OF CONDUCTION HEAT LOAD:

To reduce the conduction heat load through sample bore with same length thermal anchoring at 500 mm length from top with 1st stage of cryocooler is done, thus reducing the heat load on the sample holder

The total heat load was reduced to 0.00797 W ~ 7.97 mW by thermal anchoring.

5.1.2 RADIATION HEAT LOAD

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 radiation energy.

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

$$Q_R = \sigma F_{12} \epsilon A_{TS}(T_2^4 - T_1^4) \quad (4)$$

Radiation from vacuum jacket to thermal shield

Inner surface area of vacuum jacket $A_{VJ} = 1.75\ m^2$

Outer surface area of thermal shield $A_{TS} = 1.22\ m^2$

$$Q_R(300K - 40K) = \sigma F_{12} \epsilon A_{TS}(T_2^4 - T_1^4)$$

$$\epsilon = \frac{\epsilon_{VJ}\epsilon_{TS}}{\epsilon_{VJ} + \frac{A_{TS}}{A_{VJ}}(1 - \epsilon_{VJ})\epsilon_{TS}} \sim 0.046$$

$$Q_R = 5.67 \times 10^{-8} \times 1 \times \epsilon \times 1.22 \times (300^4 - 30^4)$$

$$Q_R = 25.76\ W$$

Radiation from thermal shield to heat exchangers

Inner surface area of thermal shield $A_{TS} = 1.21 m^2$

Outer surface area of heat exchangers $A_{HX} = 0.027\ m^2$

From equation (4) $Q_R(300K - 30K) = \sigma F_{12} \epsilon A_{HX}(T_2^4 - T_1^4)$

$$\epsilon = \frac{\epsilon_{TS}\epsilon_{HX}}{\epsilon_{TS} + \frac{A_{HX}}{A_{TS}}(1 - \epsilon_{TS})\epsilon_{HX}} \sim 0.058$$

$$Q_R = 5.67 \times 10^{-8} \times 1 \times \epsilon \times 0.027 \times (300^4 - 30^4)$$

$$Q_R = 0.719 W$$

REDUCTION OF RADIATION HEAT LOAD

Multi-layer insulation (MLI) is thermal insulation used to reduce the radiation load on the cryostat. MLI consists of aluminium (5 to 10 nm thick) on Mylar film usually with low density fibrous material between layers with very low emissivity.

MLI are normally used in vacuum system where conduction and convection loads are minimal and maximum heat load on the system is through radiation. MLI should not be compressed too tightly usually at 30 layers/cm or else the solid conduction dominates the decrease in radiation 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,

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

5.1.3 RESIDUAL GAS CONDUCTION

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.

$$\text{vacuum} \sim 5.05 * 10^{-6}\,\text{Pa}$$

$$Q_{gc} = A_{VJ}\,\alpha CP\left(T_{VJ} - T_{TS}\right)$$

$$\alpha = \frac{\alpha_{TS}\,\alpha_{VJ}}{\alpha_{VJ} + \alpha_{TS}(1 - \alpha_{TS})} \sim 0.72$$

$$Q_{gc} = 1.75 * 0.72 * 0.02 * 5.05 * 10^{-6} * (300 - 30)$$

$$Q_{gc} = 0.035\text{mW}$$

5.2 MECHANICAL DESIGN OF VTI

5.2.1 MATERIAL OF CRYOSTAT

The most commonly used material in cryogenic industry for cryostat is Stainless Steel 304 (SS 304) due to high strength and low thermal conductivity. Easily electro-polished result in clean and oxidation free surface and less contaminants is a important feature of SS 304 to use as a cryostat, since electro-polishing minimizes the effective surface area for the adsorption of gas. For vacuum tight welded joints Tungsten Inert Gas welding is used, which can easily weld SS used for ultra-high vacuum processes. The weight of the SS304 is the only drawback in application where weight is a matter of concern.

Easy availability of the SS304 and strength of stainless steel are the major reasons that it is ideal choice for the cryogenic industry for fabrication of cryostats and other commercial purpose.

Parts Sizing For Strength

Cryostats and vacuum jackets are used in pressure below atmospheric and sometime above atmospheric pressure, so it us needed to consider the proper sizing of the parts that are to be used taking into consideration the mechanical properties Basically four general guidelines are followed while designing a cryostat for mechanical strength.

1. Critical components dimensions are considered keeping the expected stress not above half of the materials yield strength.
2. To avoid buckling in case the cryostat is subjected to compression strength, wall of the cryostat should be thick enough.
3. Cryostat wall should be thick enough that it can withstand maximum load when the chamber is pressurized.
4. Limit deflection to acceptable level.

To fabricate VTI, basically we need to design heat exchanger, vacuum jacket.

5.2.2 DESIGN OF VACUUM JACKET

Vacuum jacket is a major component for thermal and mechanical design aspect of VTI. Its function is to reduce the heat load as less as for minimum heat load on the CCR. The vessel is subject to a maximum pressure upto 1 bar g, hence the thickness of the wall and end plates need to be enough to handle the axial stress and hoop stress. It is the part which supports the cryocooler thermal shield and sample tube. Top flange of the vacuum is the critical part of the vacuum jacket as maximum load is on the top flange. Vacuum jacket fails due to tensile load on plate and hoop stress due to the outside pressure as inside its vacuum.

In this case we have chosen a SS 304 sheet of thickness of 3mm.since the sheet is little bit thick its weight is increase but its overall effect on our system is negligible. The critical load that will come on the vacuum jacket.

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 = Radius of the cylinder where pressure is acting

t = Thickness of pipe

For the circular end plates, which is subjected to uniform pressure a conservative estimate, is taken that the plates are not fixed but simply supported. The bending stress σ_b acting on the centre of circular plate of thickness 't' and radius 'r' is,

$$\sigma_b = \left(\frac{3}{8}\right)(3 + \nu)Pr^2/t^2$$

$$\sigma_b \cong 1.24Pr^2/t^2$$

Dimensions of the Vacuum Jacket

Outer Diameter = 345 mm

Inner Diameter = 339 mm

Length of pipe = 460 mm

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

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

$$\frac{240 \times 10^6}{2} = P \times 0.1695/0.003$$

$$P = 21\ bar$$

As from the above solution, it is observed that the chamber can withstand upto 21 bar pressure with safety factor 2, hence all dimensions are in safe zone.as we know for pressure vessels hoop stress is twice that of axial stress, and therefore it can handle twice the pressure for the same dimensions

To calculate maximum allowable pressure on end plates. Here a conservative estimate is assumed that the edge is not fixed but simply supported.

End Plate Dimension

Diameter = 345 mm

Thickness = 15 mm

Bending Stress for End circular plate,

$$\sigma_b \cong 1.24Pr^2/t^2$$

$$\sigma_{yt}/2 \cong 1.24Pr^2/t^2$$

$$120 \times 10^6 = 1.24 \times P \times 0.1725^2/0.015^2$$

$$P = 7.3\ bar$$

In Vacuum chambers, it is inverse of the internal pressure scenario described above, in vacuum system the outer pressure tries to implode the chamber, rather than explode. The similar hoop stress and axial stress formulas are applied, except that a more safety margin is considered to limit the hoop stress to less than about 20‑25% of the material's annealed yield strength due to buckling concerns.

5.2.3 DESIGN OF HEAT EXCHANGER

Heat Exchanger is major components of the VTI system. There are three heat exchangers used in this system, to cool the gas gradually by conduction cooling using the cooling capacity of the CCR's 1st and 2nd stage. 1/8" copper tube is brazed on the copper block which is connected with the 1st and 2nd stage of the CCR. Length of the tube and contact area of the tube with the copper mass is crucial parameters that can affect the whole system and outlet temperature of the heat exchangers.

To increase the contact surface of tube and copper mass silver brazing is done. Since silver is having excellent thermal conductivity most preferable brazing is silver brazing where heat transfer is through conduction

CHAPTER 6

RESULT

6.1 EXPERIMENTAL RUN

EXPERIMENTAL RUN 1

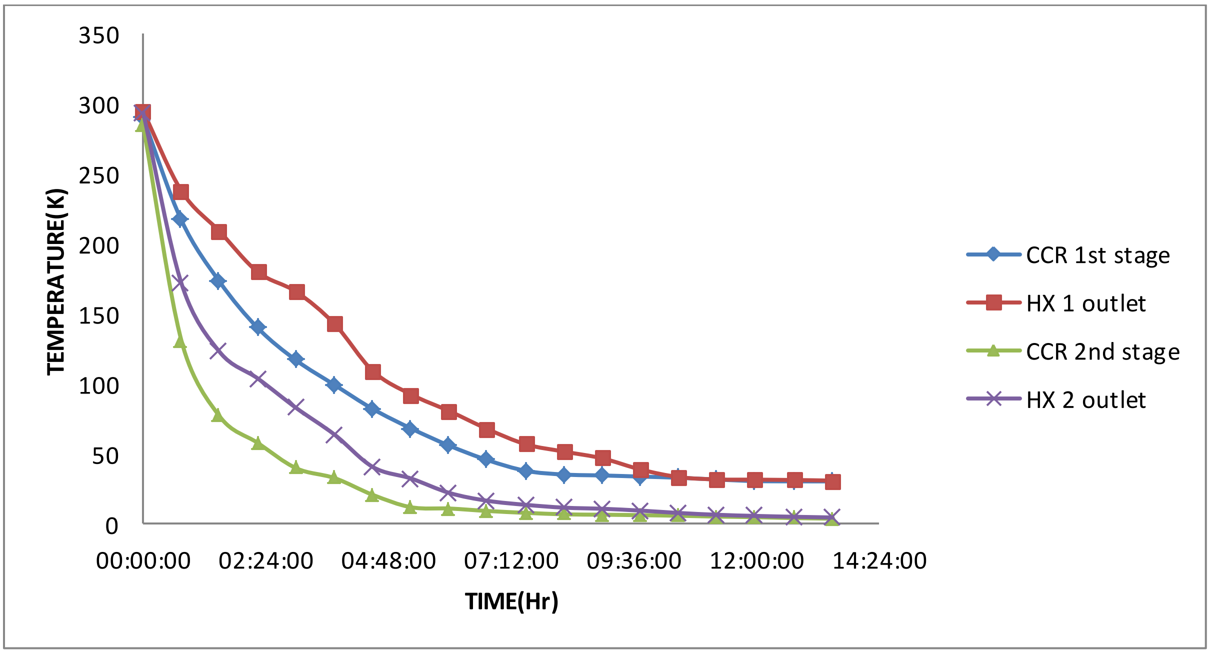

Figure 19: Experimental Run 1

Operating Pressure	15psi
Flow Rate	0.005g/s using fine control valve
Charcoal adsorber	At 1st stage of the CCR
Min Temp Achieved	4.3K
Observations	➢ Cryocooler reaches 30K 1st stage and 4.2K 2nd stage in 9hrs and achieve steady state. ➢ CCR and circulation started simultaneously. ➢ Fall in HX1 and HX2 outlet temperature for 12 Hrs and then steady state is achieved ➢ No further reduction in the temperature. Minimum temperature of 4.3K achieved.

EXPERIMENTAL RUN 2

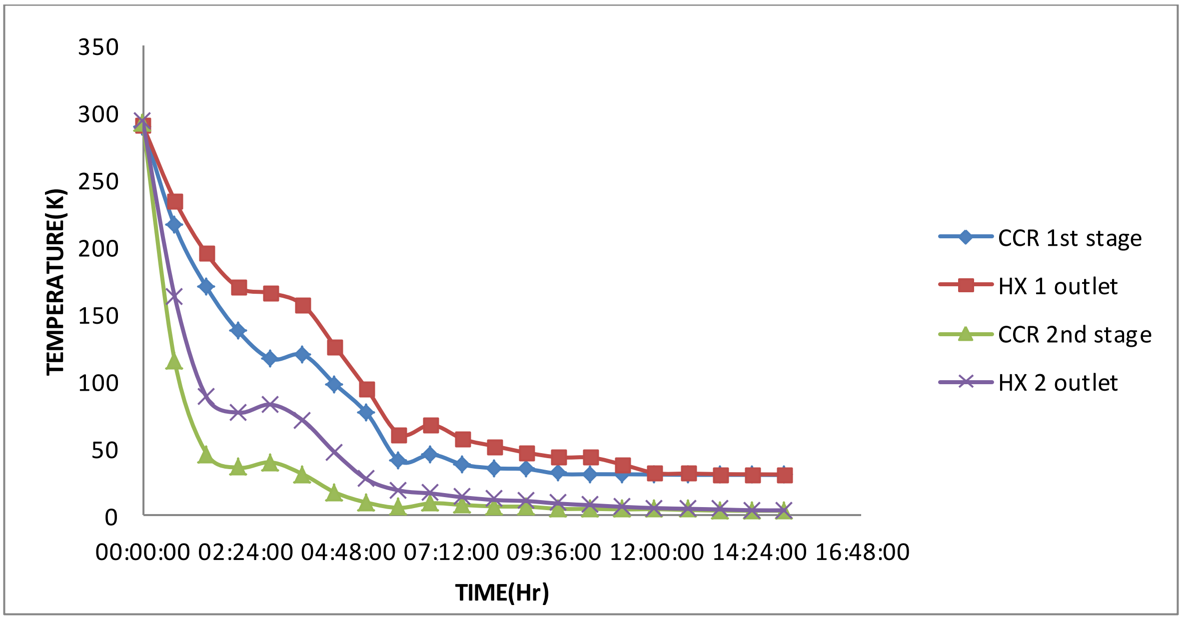

Figure 20: Experimental Run 2

Operating Pressure	15psi
Flow Rate	0.005g/s using fine control valve
Charcoal adsorber	At 1st stage of the CCR
Min Temp Achieved	4.24K
Observations	➢ Cryocooler reaches 30K 1st stage and 4.2K 2nd stage in 9hrs and achieve steady state. ➢ CCR and circulation started simultaneously. ➢ Fall in HX1 and HX2 outlet temperature for 12-13 Hrs and then steady state is achieved ➢ No further reduction in the temperature. Minimum temperature of 4.24K achieved.

EXPERIMENTAL RUN 3

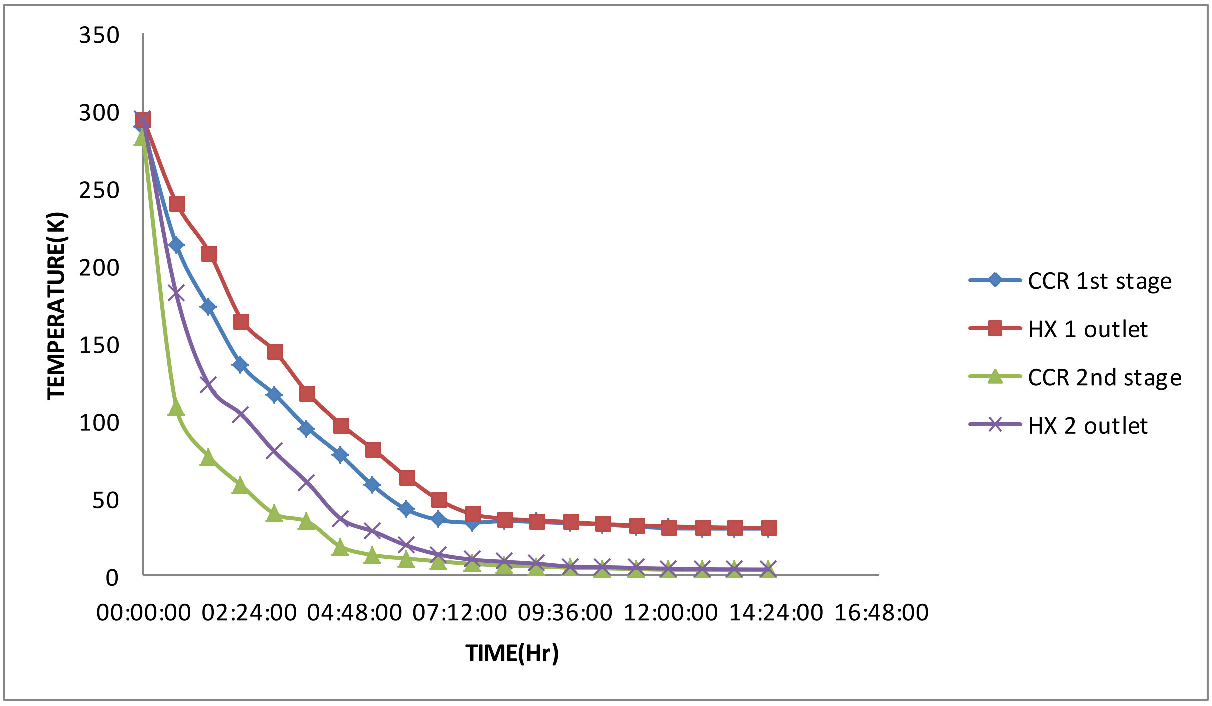

Figure 21:Experimental Run 3

Operating Pressure	15psi
Flow Rate	0.005g/s using fine control valve
Charcoal adsorber	At 1st stage of the CCR
Min Temp Achieved	4.27K
Observations	➢ Cryocooler reaches 30K 1st stage and 4.2K 2nd stage in 8hrs and achieve steady state. ➢ CCR and circulation started simultaneously. ➢ Fall in HX1 and HX2 outlet temperature for 12 Hrs and then steady state is achieved ➢ No further reduction in the temperature. Minimum temperature of 4.27K achieved.

6.2 ANSYS ANALYSIS

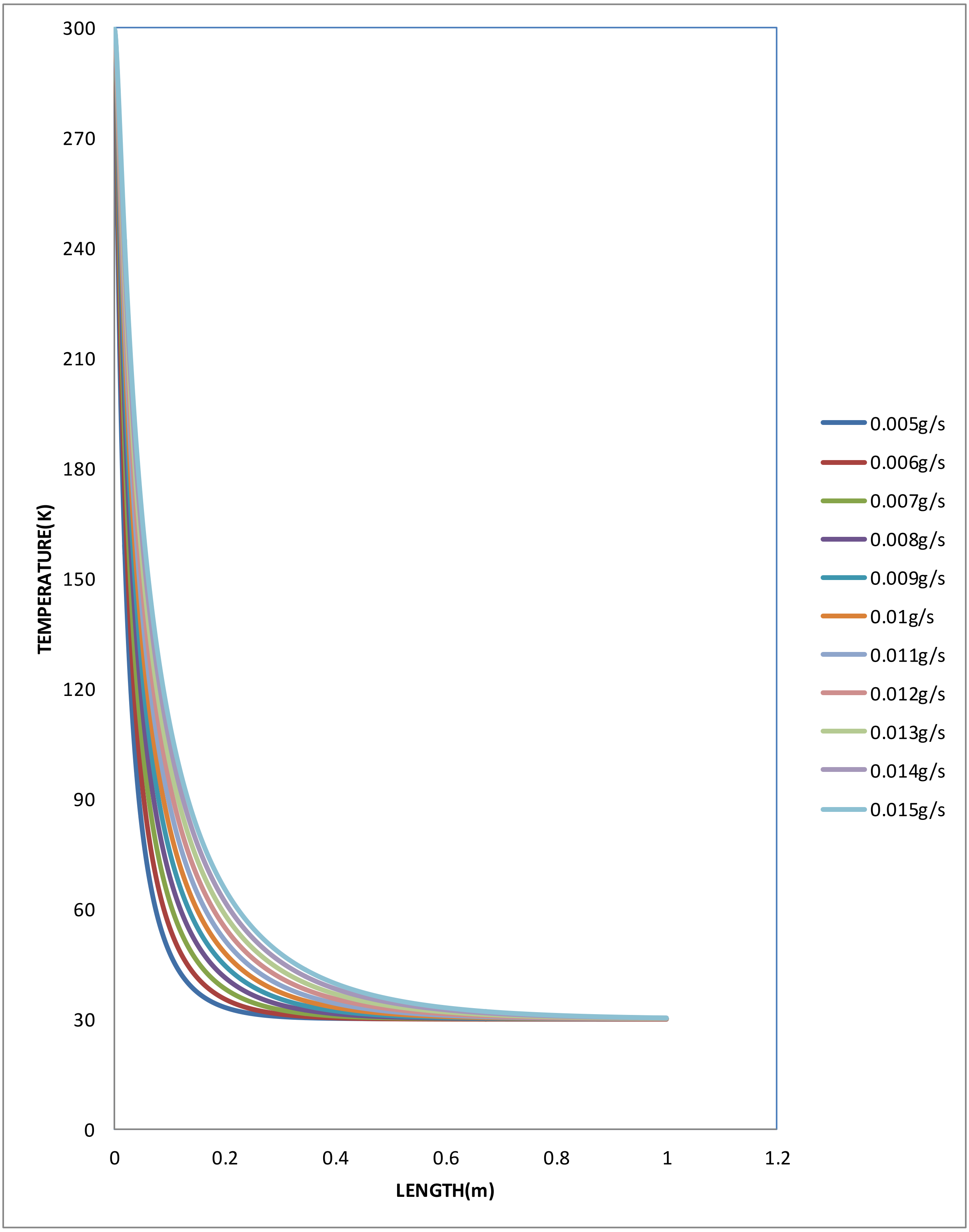

Figure 22: Ansys result at different flow rate for inlet temperature 300K

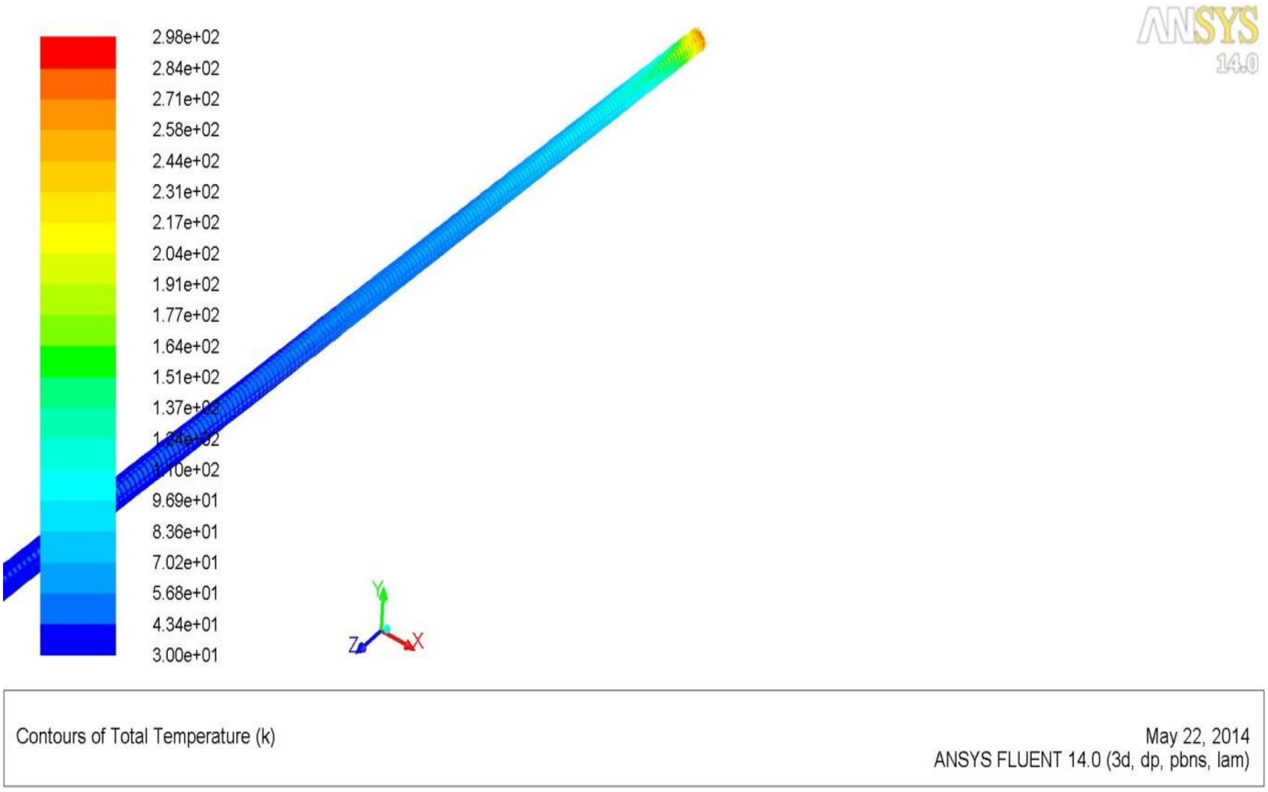

Figure 23: Temperature Contour for inlet temperature 300K

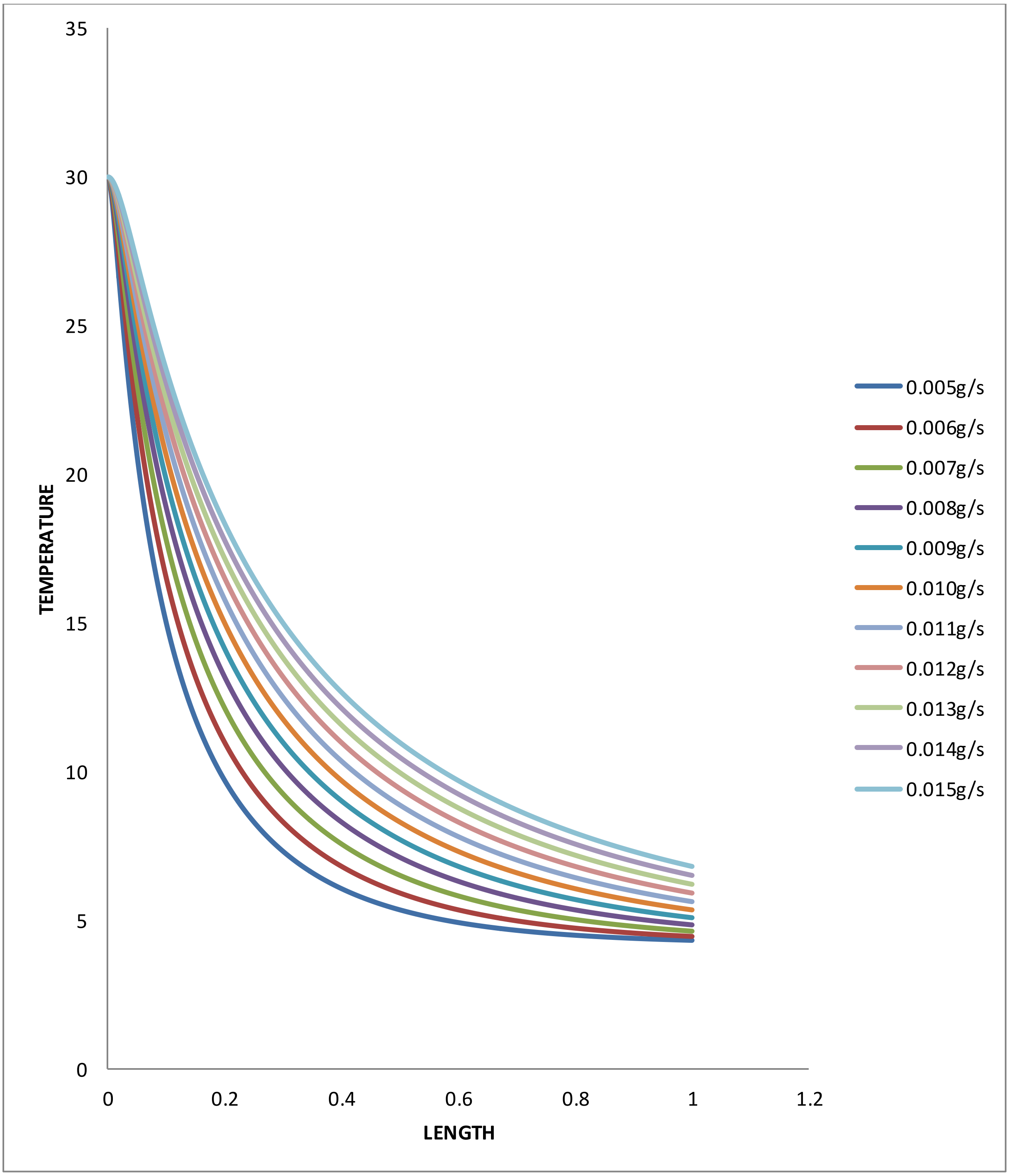

Figure 24: Ansys result at different flow rate for inlet temperature 30K

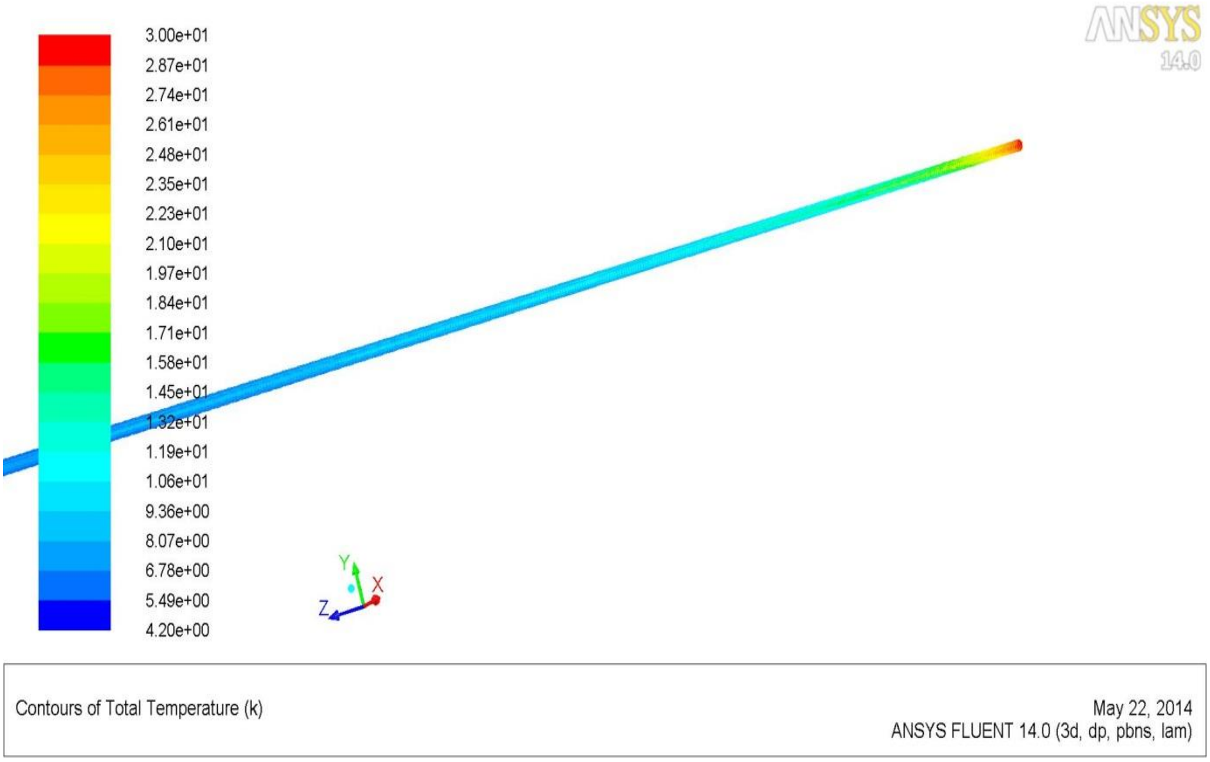

Figure 25: Temperature conture for inlet temperature 30K

6.3 HEAT LOAD AT DIFFERENT FLOW RATE

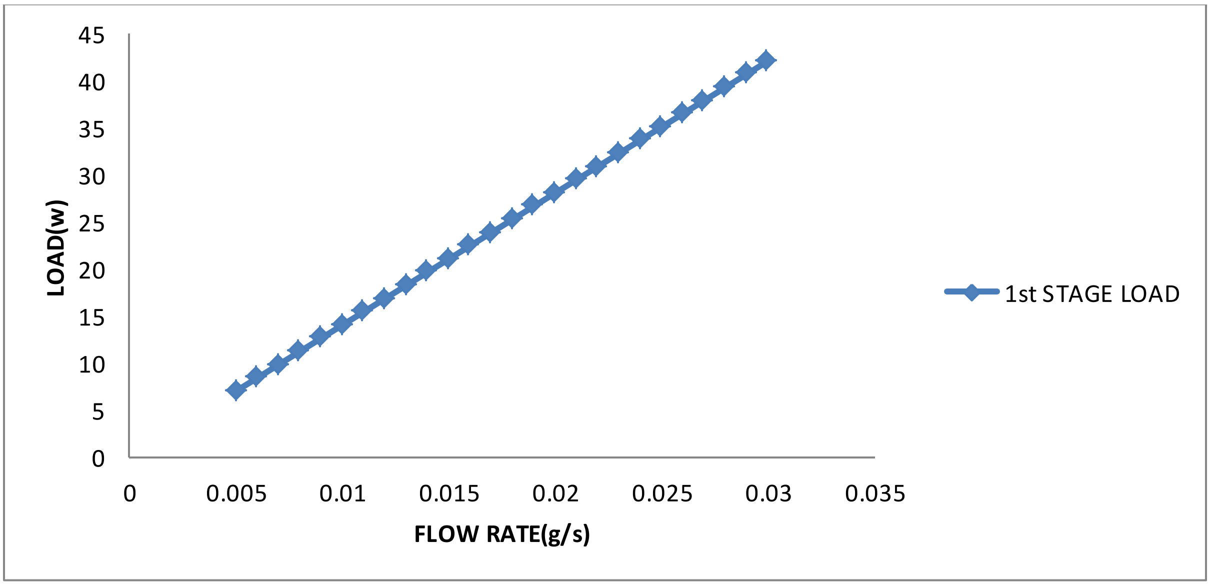

Figure 26: Load on 1st stage of CCR at different flow rate

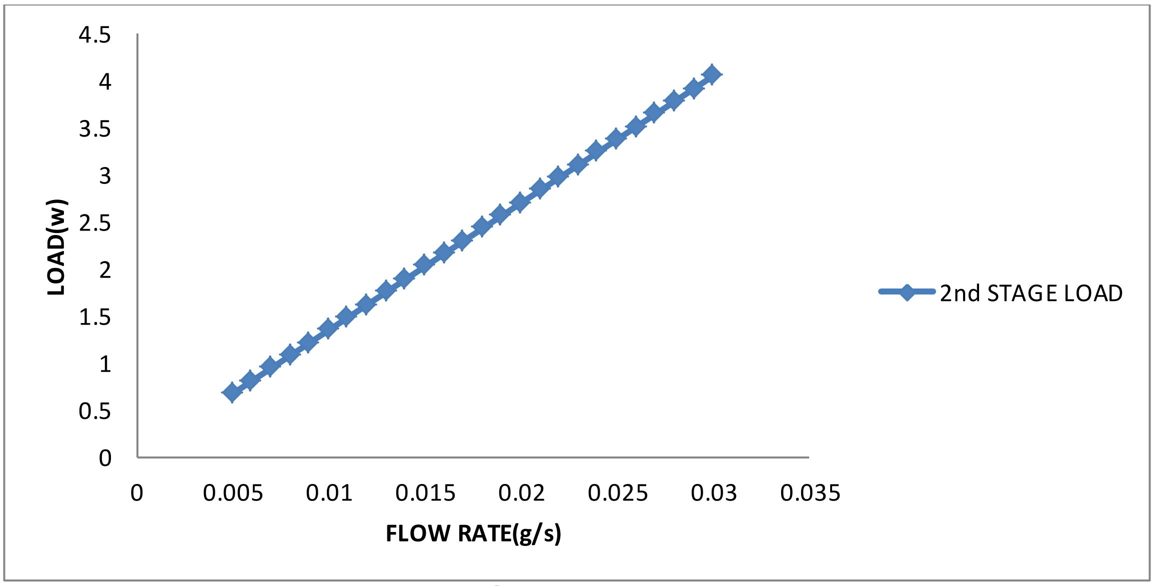

Figure 27: Load on 2nd stage of CCR at different flow rate

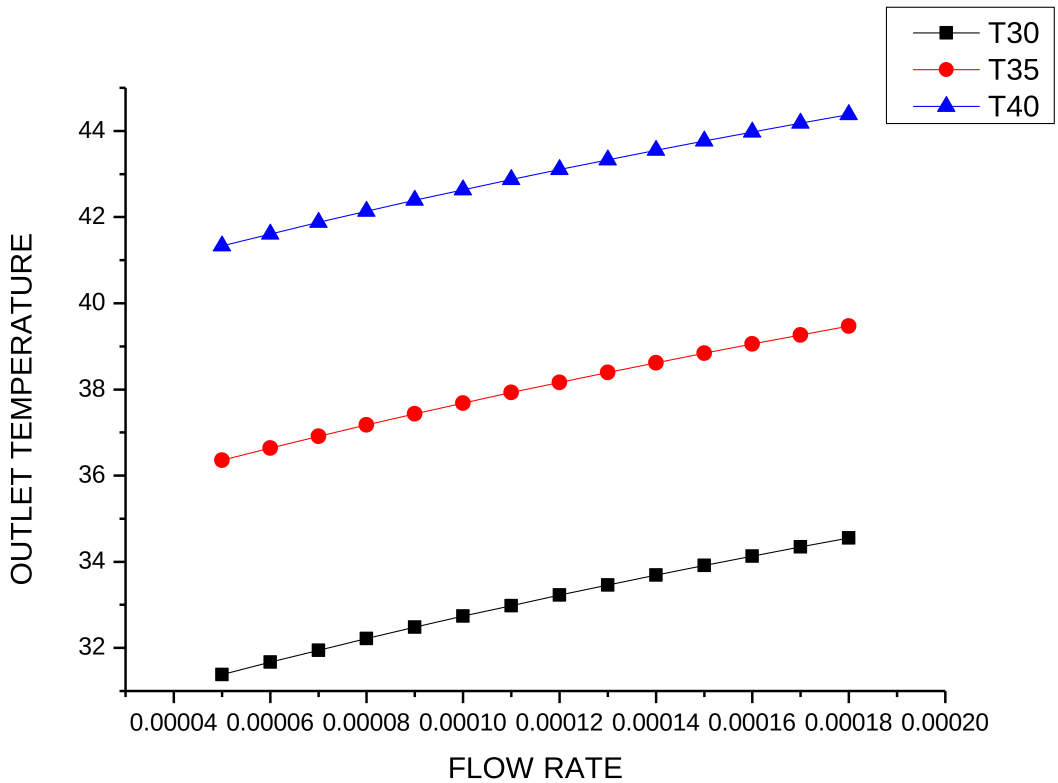

Figure 28: Outlet tempertature at different flow rate and different heat exchanger tempeature

The above graph shows the effect of inlet temperature with different mass flow rate in a 100cm long tube

After circulation of gas for nearly 14 hrs. Sample space temperature of 4.2 K is achieved. Fine control valve and other parameters are kept constant as tests are already perform on experimental test setup and regulation of flow is done. The system is completely blockage free as the highly pure gas is circulated in the whole system. System is run for several times and sample space temperature is observed.

The final run data of the VTI system is presented in Table

S.No.	Run time(Hr.)	2^{nd} Heat Exchanger(K)	Sample space temperature (K)
1	14	3.90	4.30
4	14	3.80	4.24
5	15	3.85	4.27

Table 1:Experimental Run Results

The results show that in all the runs the sample space temperature varies between 4.2 K to 4.3K at a flow rate of 0.005g/sec, which means the VTI system can be used in CFMS to vary the sample space temperature from 4.2K to 300K using heater placed on the 3^{rd} heat exchanger.

CHAPTER 7

CONCLUSION & FUTURE SCOPE

7. CONCLUSION

The variable temperature insert is designed to vary the sample space temperature of the cryogen free superconducting magnet from 300K to 4.2K by cooling helium gas using cryocooler. In our experimental test setup, which is locally fabricated at IUAC to validate the design parameters, we are able to achieve a minimum temperature of 14K due to some limitation and improper brazing of heat exchangers. But in experimental setup which is fabricated by experts gave desired result.

Summarizing the present development and significance of the present investigation.

- Performance of the variable temperature insert is tested and gives significant results.
- Heat exchangers analysis has been done and performance of the heat exchangers is up to the mark.
- Analysis of flow rate has been done and optimum flow rate is considered to minimise the heat load on the cryocooler.
- This variable temperature insert can be used commercially for variable sample space temperature in cryogen free superconducting magnet systems.

FUTURE SCOPE

- 300K to 4.2K is successfully achieved
- Experiments are to be performed at different temperature between 4.2K to 300K and magnetic field 0T to 6T.
- Efforts can be done to achieve 1.6K using condenser and J-T valve
- After successful test with two cryocooler, whole system VTI & magnet system with single cryocooler can done.

REFERENCES

[1] Cryogenic systems by Barron, R.F. (1985)

[2] Experimental Techniques in Low-temperature physics by G.K.White

[3] Experimental techniques for low temperature measurements by J.W.Ekin

[4] Matter and methods at low temperature- Frank Pobell

[5] Fundamentals of heat and mass transfer- Incropera 6th Edition

[6] A Heat transfer textbook by J.H.Lienhard

[7] Introduction To Laboratory Cryogenics By M.N. Jirmanus, Ph.D. Janis Research Company, Inc

[8] The Gifford-Mcmahon Cycle By W.E.Gifford 1965 Cryogenic Engineering Conference.

[9] Cryocoolers: The State Of The Art And Recent Developments By Ray Radebaugh National Institute Of Standards And Technology

[10] Z.J.J. Stekly, R. Thome, and B. Strauss, "Principles of stability in cooled superconducting magnets"

[11] O. Kirichek, "impact of the cryogen free revolution on neutron scattering laboratories"

[12] G. R. Chandratilleke, Y. Ohtani, H. Hatakeyama, T. Kuriyama and H. Nakagome "Gas—Gap Thermal Switch for Precooling of Cryocooler— Cooled Superconducting Magnets", Advances in Cryogenic Engineering, Vol. 41, pp. 139-146,1996.

[13] M. A. Green, "The Effect of Low Temperature Cryocoolers on the Development of Low Temperature Superconducting Magnets", ieee transaction on applied superconductivity, vol. 11, No. I, pp. 2615-2618, 2001.

[14] C. Leighton, a John Kern, and Suzanne R. English, "A high temperature probe operating in the variable temperature insert of a commercial superconducting magnet system", Rev. Sci. Instrum., Vol. 73, No. 6, pp.2364-2368, 2002.

[15] B. Evans, R. Down, J. Keeping, O. Kirichek and Zoe Bowden, "Cryogen-free low temperature sample environment for neutron scattering based on pulse tube refrigeration", Meas. Sci. Technol. 19,034018,pp.1-3 , 2008.

[16] Yeon Suk Choi, Dong Lak Kim, Byoung Seob Lee, Hyung Suk Yang, and Thomas A. Painter, "Conduction-Cooled Superconducting Magnet for Material

Control Application", ieee transaction on applied superconductivity, vol. 19, No. 3,pp.2190-2193, 2009.

[17] Kirichek, B E Evans, R B E Down, Z A Bowden, "Cryogen free low temperature sample environment for neutron scattering experiments", Journal of Physics: Conference Series 150,012022,pp. 1-4,2009.

[18] Yeon Suk Choi, Dong Lak Kim, Hyung Suk Yang, and Jae Hwi Kim, "Fabrication and Test of a Cryocooler Directly Cooled NbTi Superconducting Magnet", ieee transaction on applied superconductivity, vol. 20, No. 3, pp. 620-623,2010

[19] Demikhov E, Kostrov E, Lysenko V, Piskunov N and Troitskiy V, "8 T cryogen free magnet with variable temperature space", Journal of Physics: Conference Series, Volume 234, Issue 3, article id. 032031, pp.1-6 ,2010.

[20] Ho-Myung Chang, Seung Hoon Ryu, "Heat exchanger for subcooling liquid nitrogen with a regenerative cryocooler", Cryogenics, Volumne 51, pp.132–138,2011.

[21] Baozhi Zhao, Qiuliang Wang, Lankai Li, Haoyang Liu, Shunzhong Chen, Yinming Dai, Yuanzhong Lei, Hui Wang, and Zhipeng Ni, "Practical Application of Gas-Gap Thermal Switch in Conduction Cooled Superconducting Magnet System", ieee transaction on applied superconductivity, vol. 22, No. 3, 2012

[22] Robert A. Slade, Benjamin J. Parkinson, and Rowan M. Walsh, "Test Results for a 1.5 T MRI System Utilizing a Cryogen-free YBCO Magnet", ieee transaction on applied superconductivity, vol. 24, No. 3, 2014.

[23] www.aml-tech.com/Cryogenic-A/cryogen-free-systems.html

[24] http://www.americanmagnetics.com/datasheets%5CCryogen_Free_Magnets_Info_Brief.pdf

[25] http://www.cryomagnetics.com/

[26] http://www.shicryogenics.com/

[27] http://www.hms-beagle.com/MSDS/Wood's_Metal.pdf