Thermal Performance Analysis of Cryogenic System for Cooling of Superconducting Magnets at 4K Temperature Level

By

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DEPARTMENT OF MECHANICAL ENGINEERING

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Thermal Performance Analysis of Cryogenic System for Cooling of Superconducting Magnets at 4K Temperature Level

Major Project Report

Submitted in partial fulfillment of the requirements

For the Degree of

Master of Technology in Mechanical Engineering

(Thermal Engineering)

By

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Guided By

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May 2015

Declaration

This is to certify that

1. The thesis comprises my original work towards the degree of Master of Technology in Thermal Engineering at Institute of Technology, Nirma University and has not been submitted elsewhere for a degree.
2. Due acknowledgment has been made in the text to all other material used.

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Undertaking for Originality of the Work

I, Amit Bisht, Roll. No. 13MMET30, give undertaking that the Major Project entitled “Thermal Performance Analysis of Cryogenic System for Cooling of Superconducting magnets at 4K Temperature Level” submitted by me, towards the partial fulfillment of the requirements for the degree of Master of Technology in Mechanical Engineering (Thermal Engineering) of Nirma University, Ahmedabad, is the original work carried out by me and I give assurance that no attempt of plagiarism has been made. I understand that in the event of any similarity found subsequently with any published work or any dissertation work elsewhere; it will result in severe disciplinary action.

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This is to certify that the Major Project Report entitled “Thermal Performance Analysis of Cryogenic System for Cooling of Superconducting magnets at 4K Temperature Level” submitted by AMIT BISHT **(13MMET30)**, towards the partial fulfillment of the requirements for the award of Degree of Master of Technology in Mechanical Engineering (Thermal Engineering) of Institute of Technology, Nirma University, Ahmedabad is the record of work carried out by him under our supervision and guidance. In our opinion, the submitted work has reached a level required for being accepted for examination.The result embodied in this major project, to the best of our knowledge, has not been submitted to any other University or Institution for award of any degree.

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Amit Bisht

Abstract

Cryogenics, the science and technology of temperatures below 123 K, involves the design and development of systems and components which produce, maintain and utilize low temperatures. Present day applications of cryogenic technology are widely varied, both in scope and magnitude. One of the areas which involve cryogenic application is in fusion devices. Cryogenic system in fusion research tokamak integrates many components, i.e., heat exchangers, valves, cold circulating pumps, cold compressor etc., in various configurations for the cooling of superconducting (SC) magnets like Toroidal Field (TF), Poloidal Field (PF) and Central Solenoid (CS). Helium refrigerator/liquefier (R/L) serves as a source of cold power for the cryogenic cooling of magnets at 4 K temperature level. However, normally the cryogenic cooling to the SC magnets are accomplished indirectly using the secondary circuit by the use of cold circulating pump, which circulates the super-critical helium in closed circuit and rejects the heat from SC magnets to the Liquid Helium (LHe) bath which is maintained at ~4 K temperature level by the helium (R/L). This arrangement provides flexibility for the operation of SC magnets, which operates in pulsed manner, and still establishes stable operation for the helium (R/L). The LHe bath temperature is maintained using the cold compressor by achieving desired pressure in the LHe bath. There are various configurations that are possible for LHe bath and cold compressor arrangements, i.e., there is a common LHe bath for all SC magnets or individual bath for each SC magnet with either individual cold compressor or common cold compressor for each bath. The objective of the optimum configuration is to maintain the SC magnets below the critical temperature despite pulse heat load nature of fusion research tokamaks. Thermal system modeling and analysis of the different cryogenic cooling configuration reveals the optimum configuration satisfying the main function of cryogenic cooling of SC magnets with required thermal performance.

The modeling of the cryogenic system is done using ASPEN HYSYS 7.1 software, and is a very useful tool for checking various configuration and observing the effects of the changes on the whole system. The modeling of the cryogenic system is based on helium which is first done in steady state simulation and then in dynamic simulation. The steady state simulation result is verified with that of the analytical values calculated from HEPAK. The dynamic simulation for various system configurations was conducted using the software.

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Nomenclature

	Acronym
He	Helium
SC	Superconducting
TF	Toroidal Field
PF	Poloidal Field
CS	Central Solenoid
LHe	Liquid Helium
ST	Structure
SHe	Super-critical Helium
HEX / HX	Heat Exchanger
CC	Cold Compressor
CCB	Cold Compressor Box
SHe	Super-critical Helium
J - T	Joule Thompson
ITER	International thermonuclear experimental research
DA	Domestic Agency
MRI	Attractive reverberation imaging
NMR	Atomic attractive reverberation
MEG	Magnetoencephalography
Nb3sn	Niobium - tin
Nbti	Niobium - titanium
	Symbols
K	Kelvin
° F	Degree Fahrenheit
° C	Degree Celsius
%	Percentage
η	Efficiency (%)
kW	kilowatt
kPa	kilo pascal
MA	Mega ampere
kv	Kilo volt
	Suffix
1	Inlet/Inside
2	Outlet/Outside

Chapter 1

Introduction

1.1 Nuclear Fusion Reactor

Reactors for atomic combination are of two main varieties , magnetic confinement reactors and inertial confinement reactors. The techniques for making combination reactors are generally directed by the way that the temperatures included in atomic combination are very high to be contained in any material container.The procedure of the magnetic confinement reactor is to restrict the hot plasma by method of magnetic fields which keep it ceaselessly in circling ways which don't touch the wall of the container. This is epitomized by the tokamak outline, the most acclaimed illustration of which is the TFTR at Princeton.the method of the inertial confinement reactor is to put such high energy density into a little pellet of deuterium-tritium that it melds in such a brief time, to the point that it can't move considerably. The most exceptional test reactors include laser combination, especially in the Shiva and Nova reactors at Lawrence Livermore Laboratories.

1.1.1 Tokamak

A tokamak (токамак) is a gadget utilizing a magnetic field to restrict a plasma fit as a fiddle of a torus. Achieving a stable plasma harmony obliges magnetic field lines to move around the torus in a helical shape. Such a helical shape can be produced by including a toroidal field and a Poloidal field. In a tokamak, the toroidal field is created by electromagnets that encompass the torus, and the Poloidal field is the aftereffect of a toroidal electric current that streams inside the plasma, this flow is actuated inside the plasma with a second set of electromagnets.The tokamak is one of a few magnetic/plasma confinement device and is the most-investigated subject for delivering controlled thermonuclear fusion energy. Magnetic fields are utilized for confinement since no material can withstand the amazingly very high temperature of the plasma. Tokamaks was first created in the 1950s by soviet physicists Igor Tamm and Andrei Sakharov, motivated by an unique thought of Oleg Lavrentiev.

ITER is focused around the "tokamak", which can be used to confine plasma in a doughnut-shape vacuum vessel. The fuel is a mixture of deuterium, tritium and two isotopes of hydrogen which is warmed to temperatures in abundance of 150 million°c and thus shaping a hot plasma. Strong magnetic fields are employed to keep the plasma far from the walls of cryo-stat; this is delivered with the help of super-conducting loops surrounding the vessel and through an electrical current given to the central solenoid magnet determined by the plasma. A cross-segment perspective of tokamak is shown in Fig.1.1.[3]

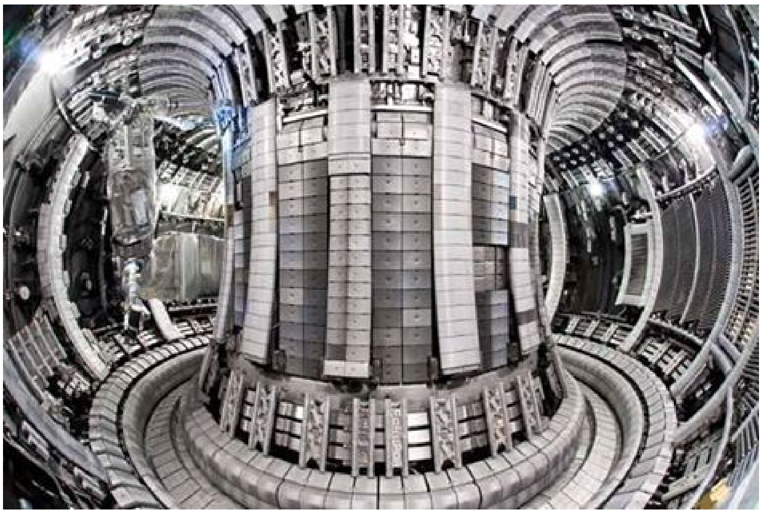


Figure 1.1: An Inside view of Tokamak [1]

1.2 Why Fusion Energy?

As the natural resources are fast depleting and fossil fuels are almost endangered there is a growing need of renewable energy or the energy which is cheap to maintain and can be distributed at reasonable prices to the masses. Energy's such as solar, wind, geothermal are helpful for the cause, but still cannot be generated in large amount. Whereas the fusion energy which is capable of generating large amount of electricity is a more viable option since a very small amount of fuel (deuterium and tritium) is required to fulfill the need of a state for an entire year. And unlike the fission nuclear reactor it does not produce harmful radioactive rays and hence is considered as a green energy.

1.3 ITER - INDIA

ITER, significance the way in Latin, is a test Fusion Reactor being developed at Cadarache, in the South of France. ITER is a step towards future creation of power from fusion vitality. Atomic Fusion is the methodology in which the Sun and the stars create the vitality by combining light cores of hydrogen. ITER will create no less than ten times more energy than the energy needed to work on it. In future demo or business reactors focused around fusion, this vitality can be changed over to electricity. A remarkable global exploratory and mechanical coordinated effort speaking to more than a large portion of the planets human populace is right away included towards development of ITER. The ITER accomplices are the People's Republic of China, the European Union, India, Japan, the Republic of Korea, the Russian Federation and the United States of America.

ITER-India is the Indian Domestic Agency (DA), structured with the obligation to give to ITER the Indian contribution.ITER will be assembled basically through in-kind commitments by the seven accomplices, significance they will construct their offer of ITER segments through a properly shaped Domestic Agency (DA) and businesses and convey them to ITER for last gathering of the gadget. India will be helping, in the same way as different accomplices aside from the host EU, around 9.1% of the ITER development cost (EU pays around 45%). The majority of this will be as segments made by the Indian business and conveyed to ITER.only a little part (~1%) will be paid in real money to a typical store for in real money acquisitions by the ITER International Team. ITER-India is the Indian DA structured to convey India's offer of Procurement Packages to ITER.[10]

1.4 Motivation For Present Study

The project considerably involves the basic fundamentals of thermodynamic, heat transfer and other subjects. One needs to acquire a considerable amount of analytical thinking to get an insight of the project. The research is all about the cooling of SC magnets such as toroidal field, Poloidal field, central solenoid and structure. As the tokamak runs for longer duration the heating of SC magnets is significant and to obtain an optimum performance from the magnets they have to be kept in their superconducting states. So the cryogenic system which is in place for the cooling of SC magnets is designed in such a way that the magnets remain in their superconducting state. The present work is about the determination of different configuration for the system, whether the system works best with a common cold compressor for TF, CS and ST or requires separate cold compressor for each magnets. The validation will be done using process modeling software and the best configuration will be selected at ITER-INDIA.

Since the project is on a global scale and to be a part of such project is a real boost to your knowledge and imagination.once the reactor gets completed it will serve millions of people and meet their demands for energy. Also it will help in saving the ecosystem since it's going to produce very less emission as to compared to other gas/coal based power plants.

Chapter 2

Literature Review

This chapter reviews the literature related to the objective of thermal performance optimization of cryogenic system for cooling of superconducting magnets at 4K temperature level.

2.1 Cryogenics

The word cryogenics means, the production of icy cold, however the term is used today as a synonym for low temperatures. A sub zero temperature environment is termed as cryogenic environment because the temperature reached is underneath the time when perpetual gasses start to melt. Lasting gasses are components that remain in the vapor state and were once difficult to condense. Including others, it constitutes the so-called permanent gases like oxygen, nitrogen, hydrogen, and helium. The national bureau of standards boulder, Colorado have chosen to consider the field of cryogenics as that involving temperatures underneath −150 °C (−238 °F or 123 K). This is the legitimate partitioning line on the grounds that the typical breaking points of the alleged perpetual gas, for example, hydrogen, helium, nitrogen, neon, oxygen and air lie beneath -150 degree Celsius. A person who is involved in the components that are subjected to absolutely icy temperatures is often called as cryogenicist. In general, the temperature scales of Celsius and Fahrenheit are utilized, but a cryogenicists utilize irrefutably the temperature scales which is Kelvin (SI units) or Rankine scale (Imperial and US units).

Cryogenic innovation will be widely utilized at ITER to make and keep up low-temperature conditions for the magnet, vacuum pumping and a few diagnostics systems.the ITER magnets will be cooled with super-critical helium at 4 K (-269°c) to work at the high attractive fields fundamental for the repression and adjustment of the plasma. They will be encompassed by an extensive cryostat and an effectively cooled warm shield with a constrained stream of helium at 80 K. Moreover, huge cryo absorption boards cooled by 4 K super-critical helium will be utilized to accomplish the high pumping rates and vacuum levels in the cryostat and torus.a cryo plant on the ITER stage will create the obliged cooling power, and disperse it through a complex arrangement of cryo lines and cold boxes that make up the cryo distribution framework.

The ITER cryogenic framework will be the biggest packed cryogenic framework on the planet with an introduced cooling force of 65 kw at 4.5k (helium) and 1300 kw at 80k (nitrogen). After the Large Hadron Collider at CERN, it is the biggest cryogenic framework ever assembled. The configuration of the ITER cryogenic framework was accepted amid tests at existing offices far an[1][5]

2.1.1 History

Cryogenics created in the nineteenth century as an aftereffect of endeavors by researchers to condense the changeless gasses. A standout amongst the best of these researchers was English physicist Michael Faraday (1791–1867). By 1845, Faraday had Figured out how to condense most perpetual gasses then known to exist. His system comprised of cooling the gas by submersion in a shower of ether and dry ice and afterward pressurizing the gas until it condensed. Six gasses, then again, opposed each endeavor for liquefaction and at that time were referred to as the lasting gasses. These were hydrogen, oxygen, carbon monoxide, nitrogen, nitric oxide and methane. The honorable gasses; neon, helium, xenon, krypton, and argon were yet to be found. The known perpetual gasses, nitrogen and oxygen (the essential constituents of air), got the most consideration. For a long time examiners toiled to melt air. At long last, the end of 1877, Louis Paul Cailletet (1832–1913), a mining engineer in France and Raoul Pictet (1846–1929) a physicist in Switzerland produced the first droplets of oxygen by pre cooling the container at approximately 300 atm and allowing the gas to expand suddenly by opening a valve on the apparatus. Later, in the year 1883, the first sufficient amount of liquid oxygen was produced by Szygmunt Von Wroblewski and K. Olszewski at the University of Crakow, Poland. Various properties of permanent gases were studied in liquid state and it was found oxygen melt at 90 K and nitrogen at 77 K.

After the successful liquefaction of air, a race to condense hydrogen followed. A giant step forward in preserving cryogenics liquid was made by James Dewar in 1892, a chemistry professor at Royal Institution in London. In May, 1898 Dewar produced 20 $cm^3$of liquid hydrogen boiling in a vacuum-insulated tube, instead of a mist. In the following year, Dewar succeeded in solidifying hydrogen and hence arriving at a minimal temperature of 14 K. The last component to be condensed was helium gas. After more than ten years of low-temperature study, Heike Kamerlingh Onnes established the physical laboratory at University of Leiden in Holland in 1895. Onnes first liquefaction of $60cm^3$ liquid helium was obtained from the 360 liters of gaseous helium. The gaseous helium was obtained by heating monazite sand procured from India.[1]

2.1.2 Techniques for Producing Cryogenic Temperatures

Cryogenic environment can be created by any of these four principal techniques: heat conduction, evaporation cooling, cooling by fast expansion (the J-T impact), and adiabatic demagnetization. The initial two techniques are known as for their regular experience. The third is little known however is usually utilized in refrigeration and air conditioning, and in addition in cryogenic applications. The fourth process is utilized essentially as a part of cryogenic applications and gives a method for reaching below 0ºC. Conduction heat transfer is when at a point two surfaces are amalgamated, high temperature streams flow to the low temperature body. Conduction can happen in the middle of any manifestations of state, gas, fluid, or robust. It is fundamental in the creation of cryogenic temperatures and situations. The next technique for delivering extreme low temperature conditions is evaporation. People are acquainted with this methodology in light of the fact that this is the system through which human cool their bodies. Molecules and atoms in the vaporous state are traveling speedier than particles in the fluid state. Add heat vitality to the particles in a fluid and they will get to be vaporous. Fluid sweat on human skin acts along these lines. Sweat retains body high temperature, turns into a gas, and dissipates from the skin.[1]

2.1.3 Cryogens and their Boiling Points

Table 2.1: Boiling Points Of Gases [1]

Permanent Gas	Boiling Point		
Cryogens	F	C	K
Hydrogen	-423	-253	20
Nitrogen	-320	-196	77
Oxygen	-297	-183	90
Helium	-452	-269	4.2
Neon	-411	-246	27
Xenon	-161	-107	166
Krypton	-242	-153	120
Argon	-302	-186	87

A process makes utilization of the Joule-Thomson impact, which was found by English physicist William Thomson, Lord Kelvin and James Prescott Joule, in 1852. The Joule-Thomson impact relies upon the inter effect of pressure, temperature and volume in a gas. Any disturbance in any of the variable, will show the effect on one of the other two (or both) likewise. Joule and Thomson found, for instance, that permitting a gas to grow quickly causes its temperature to drop significantly. Decreasing the weight on a gas finishes the same impact. To cool a gas utilizing the Joule-Thomson impact, the gas is initially pumped into a holder under high weight. The compartment is fitted with a valve with a little opening. At the point when the valve is opened, the gas escapes from the compartment and extends rapidly. In the meantime, its temperature drops. The main application of J-T effect was brought to the fore by Kamerlingh Onnes in 1908 when he liquefied helium.

2.1.4 Applications

Various application of cryogenics in present day are widely varied and are listed as under: [1]

- Rocket Propulsion Systems: All the large united states launch vehicles utilize liquid oxygen as the oxidizer. The space shuttle propulsion system uses both cryogenics fluids, liquid oxygen and liquid hydrogen.

- Studies in high-energy physics: The hydrogen bubble chamber uses liquid hydrogen in the detection and study of high-energy particles produced in large particle accelerators for e.g large hadron Collider CERN.
- Mechanical Design: By utilizing the meissner effect associated with superconductivity, practically zero-friction bearings have been constructed that uses magnetic field as lubrication instead of oil or air.
- Space-simulation and high-vacuum technology: In order to produce vacuum as that of outer space, cryo pumping or freezing out the residual gasses is used to provide the ultrahigh vacuum required in space simulation chambers and in test chambers for space propulsion systems.

Other useful applications of cryogenics in different fields are given below:

- Food Processing
- Biological and medical applications
- Manufacturing processes
- Recycling of materials

2.2 Liquid Helium

The concoction component helium exists in a liquid structure just at the to a great degree low temperature of −269 °c (around 4.214 K or −452.2 °f). Its breaking point and basic point rely on upon which isotope of helium is available: the normal isotope helium-4 or the uncommon isotope helium-3. These are the main two stable isotopes of helium and when we speak of helium or liquid helium it is generally helium-4. Liquid helium has no freezing point at pressure of 1.013 kPa or 1 atm. In fact, liquid helium does not freeze under its own vapor pressure even if the temperature is reduced to absolute zero. At absolute zero, liquid helium must be compressed to a pressure of 2529.8 kPa before it will freeze. Liquid helium is colorless and odorless and has an index of refraction near that of gaseous helium.

Helium was initially liquefied on July 10, 1908, by the Dutch physicist Heike Kamerlingh Onnes in the Netherlands.[1] around then, helium-3 was obscure on the grounds that the mass spectrometer had not yet been concocted. In later decades, some liquid helium has been utilized as a cryogenic refrigerant, and liquid helium is created economically for utilization in superconducting magnets, for example, those utilized as a part of attractive reverberation imaging (MRI), atomic attractive reverberation (NMR), Magnetoencephalography (MEG), and examinations in material science. Helium can be liquefied just by utilizing the fascinating Linde-Hampson cycle, and not by less complex methods. [2]

2.2.1 Super-fluidity

Super fluidity, propensity of liquid helium underneath a temperature of 2.19°k to stream unreservedly, even upward, with minimal evident friction. Helium turns into a liquid when it is cooled to 4.2°k. Unique systems are expected to cool a substance beneath this temperature, which is close outright zero (see Kelvin temperature scale; low-temperature physical science). At the point when the temperature achieves 2.19°k, the properties of liquid helium change suddenly, to such an extent that common helium is known as helium I and helium beneath this temperature is known as helium II. The transition temperature between helium I and helium II is known as the lambda point in light of the fact that a chart of specific properties of helium takes a sharp turn at this temperature and looks like the capillary tubes that oppose the stream of normal liquids (see capillarity) and a Dewar flask loaded with helium II from a bigger compartment will discharge itself go into the first holder in light of the fact that the liquid helium streams spontaneously in an imperceptible film over the surface of the jar. The conduct of helium II can be in part seen as far as certain quantum impacts (see quantum hypothesis). Helium stays a liquid down to total zero on the grounds that its zero-point vitality is such that it can't turn into a robust without surrendering a measure of vitality that is short of what that permitted by the quantum hypothesis. Likewise, quantum limitations keep helium II from carrying on like a typical liquid on the grounds that the vitality connections connected with rubbing and thickness in ordinary liquid stream include sums unrealistic for helium. [2][9]

2.3 Tokamak Magnets and their Purpose

The ITER magnet framework embodies 18 superconducting toroidal field and 6 Poloidal field loops, a focal solenoid, and a set of rectification curls that attractively bind, shape and control the plasma inside the vacuum vessel. Extra loops will be executed to moderate Edge Localized Modes (Elms), which are exceptionally vigorous upheavals close to the plasma edge that, if left uncontrolled, cause the plasma to lose part of its vitality. A general perspective of tokamak magnets inside a tokamak is shown in Fig.2.1.[4]

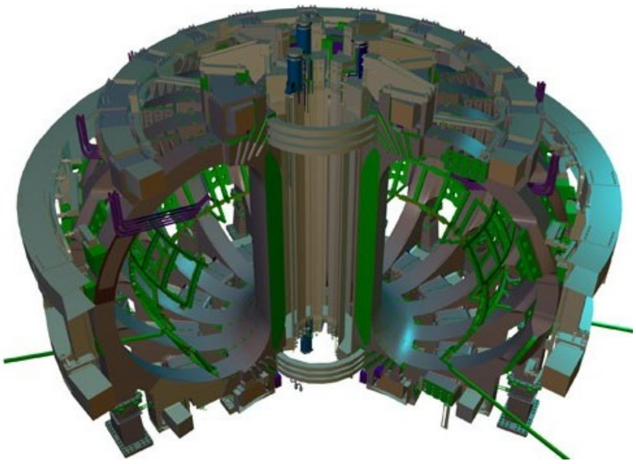


Figure 2.1: Tokamak Magnets [4]

The force of the magnetic fields needed to limit the plasma in the ITER vacuum vessel is compelling. For greatest productivity and to utmost energy utilization, ITER uses superconducting magnets that lose their safety when chilled off to low temperatures. The toroidal and Poloidal field loops lie between the vacuum vessel and the cryostat, where they are cooled and protected from the hotness creating neutrons of the fusion response. The superconducting material for both the focal solenoid and the toroidal field loops is intended to attain operation at high magnetic field (13 Tesla), and is an exceptional amalgam made of niobium and tin (Nb3sn). The Poloidal field loops and the rectification curls utilize an alternate, niobium-titanium (Nbti) amalgam. Keeping in mind the end goal to accomplish superconductivity, all curls are cooled with super-critical helium in the scope of 4 Kelvin (-269°c). Superconductivity offers an appealing proportion of force utilization to cost for the long plasma beats visualized for the ITER machine.

2.3.1 Toroidal Field System

The 18 toroidal field (TF) Fig. 2.2 magnets produce a magnetic field around the torus, whose essential capacity is to bind the plasma particles. The ITER toroidal field loops are intended to have an aggregate magnetic energy of 41 gigajoules and a greatest magnetic field of 11.8 Tesla. The curls will weigh 6,540 tons all out; other than the vacuum vessel, they are the greatest parts of the ITER machine. The curls will be made of link in-course superconductors, in which a heap of superconducting strands is cabled together and cooled by streaming helium, and contained in a structural coat. The strands vital for the ITER toroidal field curls have an aggregate length of 80,000 kilometers. [4]

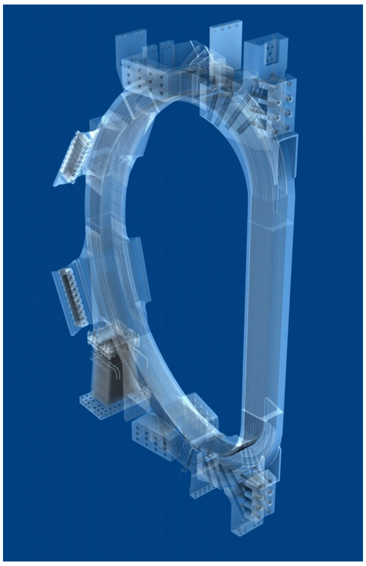


Figure 2.2: Toroidal Field [4]

2.3.2 Poloidal Field System

The Poloidal field (PF) magnets in Fig. 2.3 squeeze the plasma far from the dividers and help thus to keeping up the plasma's shape and soundness. The Poloidal field is prompted both by the magnets and by the current drive in the plasma itself. The Poloidal field curl framework comprises of six level curls put outside the toroidal magnet structure. Because of their size, the real slowing down five of the six Poloidal field curls will happen in a devoted, 257-meter-long curl slowing down on the ITER site in Cadarache. The littlest of the Poloidal field loops will be made off site and conveyed completed. The ITER Poloidal field loops are likewise made of link in-channel conductors. Two separate sorts of strands are utilized as per working prerequisites, each one showing contrasts in high-present and high-temperature behavior.[4]

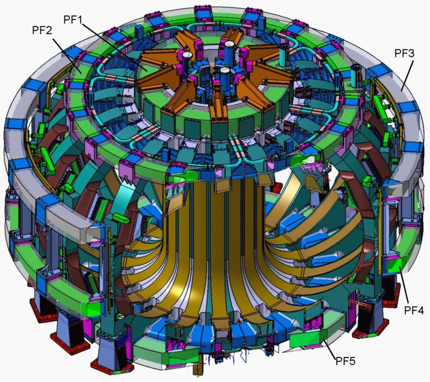


Figure 2.3: Poloidal Field [4]

2.3.3 Central Solenoid

The primary plasma current is prompted by the changing current in the central solenoid Fig. 2.4 which is basically a vast transformer, and the "spine" of the magnet framework. It helps the inductive flux that drives the plasma, to the molding of the field lines in the divertor district, and to vertical solidness control. The central solenoid is made of six free curl packs that utilize a niobium-tin (Nb3sn) link in-channel superconducting conductor, held together by a vertical pre compression structure. This configuration empowers ITER to get to a wide working window of plasma parameters, empowering the testing of diverse working situations up to 17 MA and covering inductive and non-inductive operation. Each one loop is focused around a stack of various flapjack slowing down that minimizes joints. A glass-polyimide electrical protection, impregnated with epoxy pitch, gives a high voltage working ability, tried up to 29 kv. The conductor coat material needs to oppose the extensive electromagnetic powers emerging amid operation and have the capacity to show great weariness conduct. The conductor will be delivered in unit lengths up to 910 meters.[4]

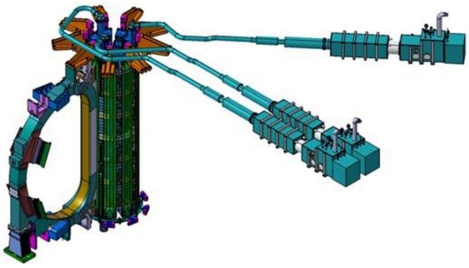


Figure 2.4: Central Solenoid [4]

2.4 Cooling System of Tokamak Magnets

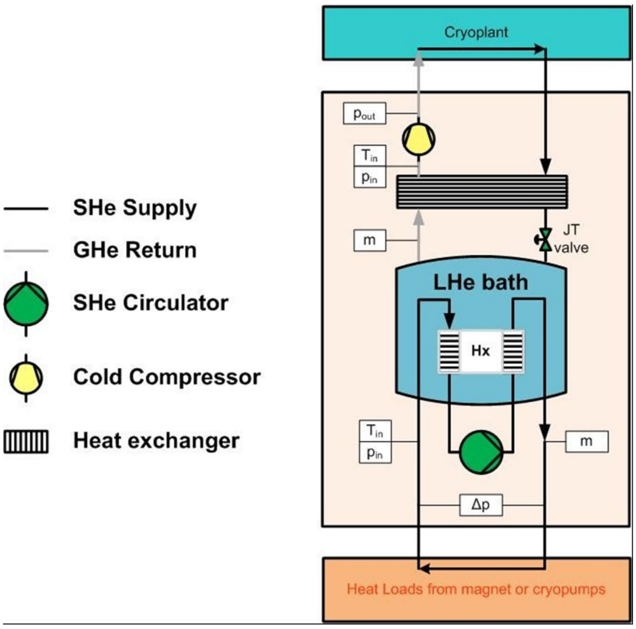


Figure 2.5: Cooling System Of Magnets [2]

As can be seen from the Fig. 2.5 the super-critical helium (SHe) comes from the cryo plant at around 4.55K and 5 bar and goes into the heat Exchanger where its temperature is further reduced with the help of incoming helium vapor at around 4.2K. From the heat exchanger the SHe then goes to the Joule-Thomson (JT) valve where it's temperature is further reduced to achieve liquid helium (LHe) at around 4.2K and 0.9923 bar. Whereas the helium vapor from the heat exchanger goes to the cold compressor where it is compressed to a pressure of 1.35 bar and is then sent to cryo plant. The LHe is then stored in a tank where two heat exchanger are placed which dump the heat load into the LHe tank. In the lower loop the LHe takes the heat load generated by the magnets and keeps it in the superconducting state and the heat load is dumped by the heat exchanger in LHe tank. A cold circulator pump is placed between the two heat exchanger to compensate for the pressure drop in the cryo lines and the heat load generated due to the pressure rise in the cold circulator pump also the heat in leak form ambient is again dumped by another heat exchanger in the LHe tank.[2][12]

2.5 List of research papers studied and remarks on ASPEN HYSYS dynamic simulation

The following table 2.2 shows various research papers studied for better understanding of the work carried out by various person in the field of dynamic simulation using ASPEN HYSYS 7.1 including the author name and title of the paper with concluding remarks.

Table 2.2: Research papers on dynamic simulation

Sr. No	Name of Author(s)	Research paper/book/Article Title	Remarks
1.	Rohan Dutta, P. Ghosh, K. Chowdhury	Customization and validation of a commercial process simulator for dynamic simulation of Helium liquefier	In this paper the author has simulated the helium plant for normal and cool down operation using ASPEN HYSYS 7.0 which matched the operational data very closely. During simulation various problems like thermo-physical and thermodynamic properties of the fluids also the estimation of equipments sizing was explained.
2.	R. Dutta, P. Ghosh, K. Chowdhury	Design and analysis of large-scale helium liquefiers/refrigerators: Issues with modeling and simulation	In this paper the author has simulated the large scale helium refrigerator/liquefier using different software like ASPEN PLUS/Dynamics, ASPEN HYSYS and ChemCAD. The author selected ASPEN HYSYS due to its more ease in simulating the system in steady state as well as dynamic state.
3.	R.J Thomas, R. Dutta, P. Ghosh, K. Chowdhury	Applicability of equations of state for modeling helium systems	In this paper the author simulated the collins cycle using different equation of state like MBWR, Peng-robinson and EOS proposed by Mann. The simulation time using MBWR-PR EOS is found to be faster than using MBWR EOS alone.
4.	R. Dutta, P. Ghosh, K. Chowdhury	Identification of critical equipment and determination of operational limits in helium refrigerators under pulsed heat load	The large-scale helium refrigerator is simulated at 120 W at 4.2 K and another of 18 W at 4.2 K under pulsed heat load condition and it was observed that high fluctuation of return stream mass flow rate back to the refrigerator resulted in the tripping of coldest turbine and depleted liquid percent level in dewar vessel.

5.	R. Dutta, P. Ghosh, K. Chowdhury	Mitigation of effects of pulsed heat load from fusion devices on helium refrigerator: A novel technique using vapor compression cycle	This paper explains the helium refrigerators are subjected to pulsed heat load which causes high fluctuation in return stream mass flow. Various mitigation technique shows mitigation of 70% and 90% mass flow during high and low heat load condition respectively.
6.	R. Dutta, P. Ghosh, K. Chowdhury	Mitigation of Effects of Pulsed Heat Loads in Helium Refrigerators for Fusion Devices Using Supercritical Helium Storage	This paper explains the advantages of super-critical helium over sub-critical helium. And a mitigation technique using a modified-calude-cycle based refrigerator dynamically simulated in ASPEN hysys which can achieve mitigation of about 78% and 74% in return stream mass flow fluctuation under high and low heat load.
7.	R.J Thomas, R. Dutta, P. Ghosh, K. Chowdhury	Dynamic Simulation of Helium Liqufiers using Aspen Hysys: Problems, Solutions and Prospects	In this paper two helium liqufier with capacities of 100 L/hr and 50 L/hr with and without liquid nitrogen pre-cooling has been simulated using ASPEN hysys. The cool-down process has been simulated from 300 K to 8 K showing similar trends in the temperature variations at different state points.

Chapter 3

ITER Cryogenic System and its Modeling

In this chapter, we are going to look at the configuration of the cryogenic system and study in detail the working of the system as well as perform analytic calculation of the system at a burn time of 100 seconds. Before the calculation is done, it is important to know about the HEPAK software which can calculate helium intrinsic properties form 0.8 K to 1500 K and is a useful software for the solving of cryogenic system and has been discussed at the beginning.The modeling of cryogenic system will be done using ASPEN HYSYS 7.1 and will be modeled in steady-state as well as dynamic simulation. The use of this software is recommended as other software's lack steady state to dynamic simulation transition or event scheduler for varying heat loads in magnet w.r.t time as described in [12] [14][15]

3.1 HEPAK Software

It's a computer program for calculating the thermo physical properties of helium from fundamental state equations. The state equations are valid from 0.8K or the melting line to 1500K including the super fluid region, the lambda line and liquid vapor mixtures. As a function of pressure the equations are valid up to 1000 bar except in the temperature range of 80K to 300K where the state equations are valid to 1000 bar. HEPAK likewise incorporates warm transport properties in both ordinary and super liquid, the dielectric steady, refractive list, and liquid surface strain. The client of HEPAK ought to be proficient in thermo physical ideas as connected to liquid properties. The creator of the HEPAK project is Dr. Vincent Arp.[11]

3.1.1 HEPAK Functions Available in Excel

A few HEPAK capacities are accessible to the Excel client through the HEPAK.xla include:

- HeCalc This is the essential capacity that profits the computed estimation of any chose thermodynamic capacity at a given state point.

- HeRefrac This capacity gives back the refractive record. It varies from HeCalc in that the wavelength is an information parameter notwithstanding the two thermodynamic data parameters needed (by HeCalc) to characterize a state point. HeMsg This profits a brief sentence depicting either (a) the liquid stage (single stage liquid, immersed fluid, or fluid vapor blend) at a given state point taking after a fruitful computation, or (b) a mistake message if the count fizzles at that state point.

- HeUnit This profits a name giving the units for any chose thermodynamic parameter. The client chooses from four unique units sets.

- HeConst This profits different parameters: atomic wt, basic point parameters, lambda point parameters, and so on. HeProperty This profits the property name for that property record.

- HeValidate This profits a message demonstrating a substantial/invalid data pair.

Out of these HEPAK capacities "HeCalc" will be utilized the most and its linguistic structure and utilization will be contemplated in the present study.

3.1.2 Function HeCalc

=HeCalc(Index, Phase, Input1, Value1, Input2, Value2, Unit)

HeCalc is the capacity that calls the HEPAK systems and returns an ascertained thermodynamic property to the calling spreadsheet cell. HeCalc returns one and only numeric worth to the spreadsheet cell. A sum of seven parameters must be determined in the calling contention list. The initial two parameters characterize the property to be computed. The following 4 parameters characterize the thermodynamic information values, and the last parameter characterizes the units for both info to and yield from HEPAK:

List is a number somewhere around 0 and 39 (comprehensive) that indicates the liquid property to be come back to the calling spreadsheet cell. A rundown of liquid properties and their relating Index is given underneath. For reference few index's are given in Table 3.1 :

Table 3.1: HEPAK Index[8]

Property Index	Property Name
0	Quality
1	Pressure
2	Temperature
3	Density
4	Specific Volume
5	Z = PV/RT
6	DPTSat
7	Latent Heat
8	Entropy
9	Enthalpy

Stage is a number somewhere around 0 and 5 that permits the client to indicate which liquid stage (single-stage, fluid, blend, or vapor) property is to be returned. A full clarification of this parameter takes after. A helpful default is gotten when the client sets Phase=0.

At the point when Phase=0, HeCalc gives back (a) solitary stage liquid properties when the computed liquid state is in the single-stage area, (b) fluid vapor blend properties when the state point is a fluid vapor blend, (c) soaked fluid properties when the state point is on the immersion line, unless (d) one the info parameters (Input1 or Input2) asked for immersed vapor properties. Setting Phase=0 is essentially a default setting, with the returned parameter being controlled by the figured estimation of Index.

- When Phase=1, HeCalc returns either the single-stage properties when the ascertained liquid state is in the single-stage district, or fluid vapor blend properties when the state point is a fluid vapor blend. On the off chance that the state point is either an immersed fluid or a soaked vapor, HeCalc returns "N/A".
- When Phase=2, just single-stage liquid properties are returned. In the event that the computed liquid state is a fluid vapor blend, or is on the immersion line, HeCalc returns "N/A".
- When Phase=3, just fluid vapor blend properties are returned. In the event that the state point is a solitary stage liquid, an immersed fluid or a soaked vapor, HeCalc returns
- When Phase=4, HeCalc gives back the immersed fluid properties at the weight and temperature of the computed state point. On the off chance that the ascertained state point is in the single-stage area, HeCalc returns "N/A".
- When Phase=5, HeCalc gives back the immersed vapor properties at the weight and temperature of the computed state. On the off chance that the ascertained state point is in the single-stage area, HeCalc returns "N/A".

Input1 and Value1 together determine one thermodynamic info to HEPAK. Input1 is either a number from 0 to 15 or the comparing alphabetic character(s) of that parameter. Value1 is the numeric estimation of that parameter in the units showed by the Units parameter. Input2 and Value2 are the relating amounts for the second thermodynamic variable, and take after the definitions given above for Input1 and Value1.

Units is a number from 1 to 4 which indicates the data yield units set,

Units = 1 for SI units,

Units = 2 for blended SI-cgs units,

Units = 3 for blended SI-molar units,

Units = 4 for "building" units.

For a complete sample:

=HeCalc(8, 0, "P", 100, "T", 30, 2)

gives back the entropy given that the weight, P, is 100 and the temperature, T, is 30, with units for every one of the three of these numbers being controlled by units set No 2. It is imperative to note that the info parameters can be given in either arrange, i.e.,

=HeCalc(8, 0, "T", 30, "P", 100, 2)

creates precisely the same result (= 19.644 J/g), as does the first calculation.

3.2 Heat Load Variation of the Magnets w.r.t Time

One of the main requirement for the cryogenic system is to deal with the pulse nature of the heat load. The pulsed nature of heat load is due to the operational time of the magnets. If magnets are active for a longer duration more will be the heat load and vice versa. And therefore magnets have different heat loads on the basis of their operation. Fig. 3.1 shows 2 cycles of the worst case simulated heat loads applied to the ACBs for the CS, TF, ST and PF, respectively. These curves are based on VINCENTA simulation results. Since the model includes each ACB and we can apply these loads directly to the appropriate ACB. The loads are applied in a periodic manner, in order to facilitate simulations of a series of pulses. [19]

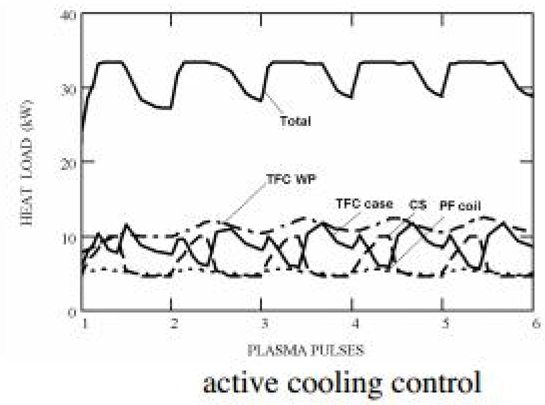
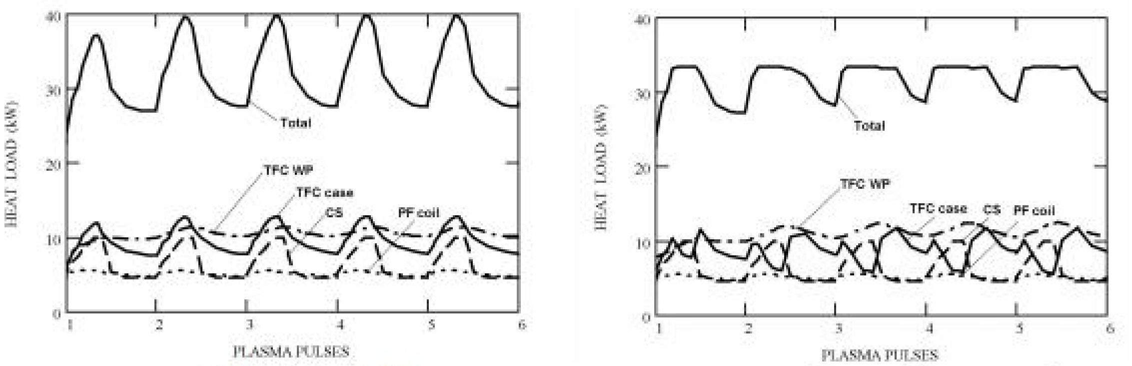


Figure 3.1: Pulse Heat Load of magnets [19]

The moment heat load from every coil and structure is figured on the premise of estimations of a helium mass stream rate and a moment variable outlet temperature (and weight) for every magnet part. The aggregate of the moment heat loads from the distinctive magnet segments is dead set on the premise of above estimations and contrasted and the normal cooling limit of the LHe plant for this plasma test. In the event that the aggregate moment heat load on the LHe plant is higher than the normal cooling limit of the LHe plant the detour valve will open in a controlled manner and a piece of the helium stream will return back to the TF cases without going through the super-basic helium heat exchanger of the TF case cooling circle. As demonstrated in Fig. 3.2 the most extreme aggregate heat load is near to 40 kW and this load shifts by around 12 kW if no dynamic cooling control is kept up. For dynamic cooling control the maximal heat load on the LHe plant is 32.3 kW. Note that the heat load for the outline purpose of the LHe plant is decided to be higher by 2 kW to incorporate a consistent state heat load anticipated from cryo lines and chilly valve boxes of the PF (Poloidal field) coils and the CS (focal solenoid).



without control

active cooling control

Figure 3.2: Heat load without control[19]

3.3 Modeling of Cryogenic System

In this we are mainly going to focus on the modeling of the cryogenic system, the modeling has been done using ASPEN HYSYS 7.1 software, it is helpful for process modeling of the cryogenic system in less amount of time and with relative ease. The modeling is first done based on the steady-state simulation and its convergence is achieved and then the dynamic simulation is carried out to verify the working of cryogenic components and its effect in the secondary loop in transient heat load conditions.

3.3.1 ASPEN HYSYS 7.1

The ASPEN HYSYS 7.1 software will be used for the steady state and dynamic simulation. The advantage of using this software is that it is very simple to simulate the steady state conditions as all the unit operations such as heat exchanger, compressor, expander, pump, streams already exists all we have to do is modify the system according to our needs. The software is divided into two parts : steady state and dynamic simulation, both are explained in the following sections.[8][15][17][18]

Steady-state:

- Process Design/Optimizations
- Equipment conceptual design
- Studying equipment and process economics
- Studying different scenarios for operation and their outputs (Case Studies)

Dynamic:

- Used to model start-up and shutdown scenarios
- Used also to model and design control systems and equipment

3.3.2 Steady - State Simulation

For creating a steady state simulation there are steps that needs to be followed and are shown step by step;

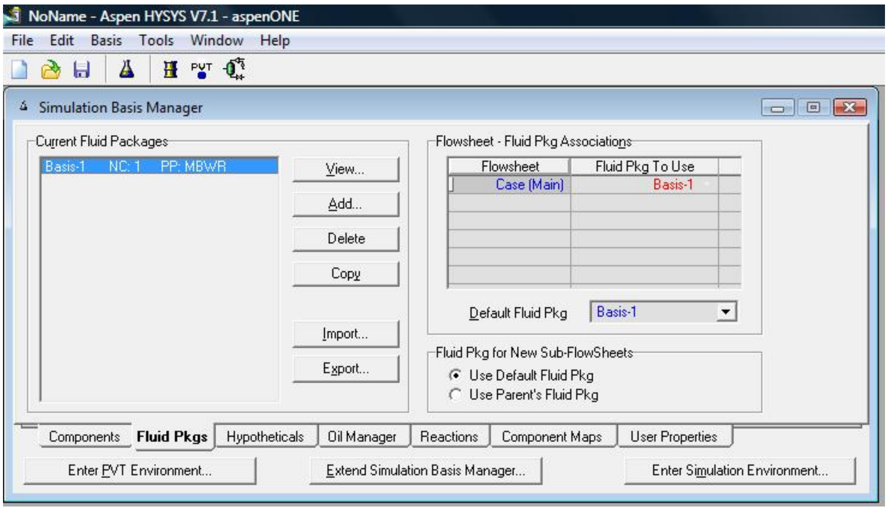
Simulation Basis Environment :

At the point when starting another simulation case, Aspen HYSYS consequently begins you in the Simulation Basis environment where you can make, characterize and alter liquid bundles for utilization by the simulation stream sheets. By and large, a liquid bundle contains at least one property bundle and library and/or theoretical parts. Liquid bundles can likewise contain data for responses and communication parameters. You can re-enter the Simulation Basis environment from any stream sheet by selecting the Enter Basis Environment charge in the Simulation menu, or tapping the Basis symbol found in the toolbar of both the Main and Column environment.

3.3.3 Simulation Basis Manager

The Simulation Basis Manager property perspective permits you to make and control each liquid bundle in the simulation. Every stream sheet in Aspen HYSYS can have its own particular liquid bundle. The format and section subflowsheets dwell inside the Main Simulation, so these subflowsheets can acquire the liquid bundle of the principle stream sheet, or you can make a totally new fluid package for every subflowsheet.

The Fig. 3.3 shows the selected fluid package for the simulation of cryogenic system. The selected fluid package is **Modified-Benedict–Webb–Rubin equation (MBWR)**, it is used because it contains the properties of helium till temperature 2K which is required for our simulation, other fluid package such as peng-robinson also contains helium properties but as compared to MBWR the variation in peng-robinson was higher and was not accurate at low temperature. Here, the property values of HEPAK was considered as a reference as it is accurate till 0.8K. [16]



Basis-1 NC: 1 PP: MBWR

Flowsheet	Fluid Pkg To Use
Case (Main)	Basis-1

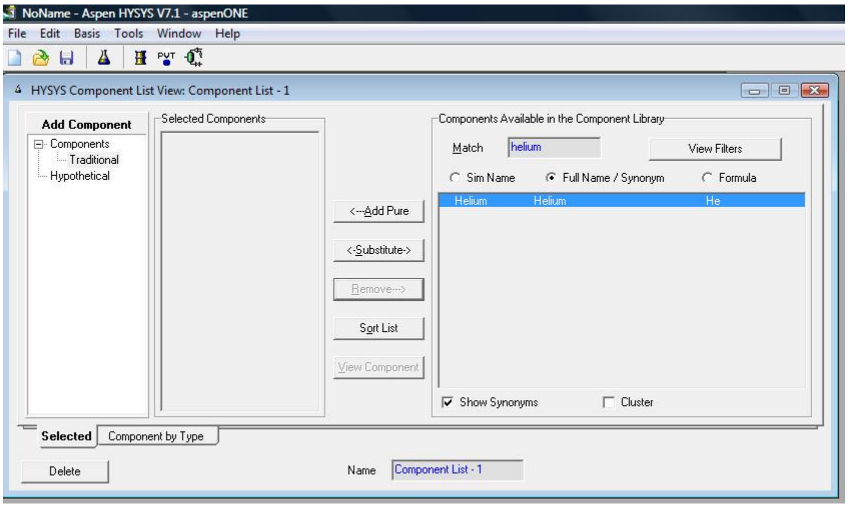
Default Fluid Pkg: Basis-1

● Use Default Fluid Pkg
○ Use Parent's Fluid Pkg

Figure 3.3: Fluid package [8]

3.3.4 Components Tab

The Components tab is the place you characterize the arrangements of substance components utilized as a part of the simulation. These part sets are put away in Component Lists and can incorporate library unadulterated components and/or speculative components.The Components tab contains a Master Component List that can't be erased. This expert rundown contains each part accessible from "all" segment records. In the event that you add components to some other segment list, they are consequently added to the Master Component List. Additionally, on the off chance that you erase a part from the expert show, it is erased from all other segment records utilizing that segment. For this situation helium is chosen as indicated in Fig. 3.4.


NoName - Aspen HYSYS V7.1 - aspenONE

HYSYS Component List View: Component List - 1

Match: helium

○ Sim Name ● Full Name / Synonym ○ Formula

Helium	Helium	He

☑ Show Synonyms ☐ Cluster

Name: Component List - 1

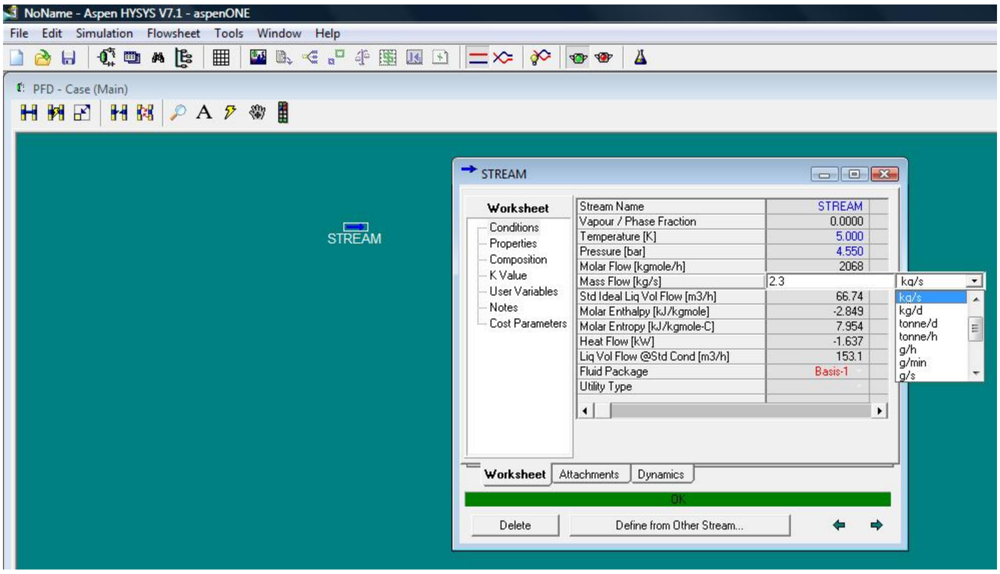
Figure 3.4: Component selection [8]

3.3.5 Entering Simulation Environment

The simulation case main flow sheet environment is where you do the majority of your work in Aspen HYSYS is performed. The following are installed and defined :

- Streams
- Unit operations
- Columns

The simulation environment is shown in Fig. 3.5 where a stream is defined and its properties is defined such as pressure, temperature, mass flow (values shown in Fig. blue colour) for a stream these three values has to be given to completely define a stream. Also the composition of the component used since we are using only one component, hence its mole fraction is set at 100%. One of the flexibility in HYSYS is the units, which are available next to the property input in a drop down list.



Stream Name	STREAM
Vapour / Phase Fraction	0.0000
Temperature [K]	5.000
Pressure [bar]	4.550
Molar Flow [kgmole/h]	2068
Mass Flow [kg/s]	2.3 kg/s
Std Ideal Liq Vol Flow [m3/h]	66.74
Molar Enthalpy [kJ/kgmole]	-2.849
Molar Entropy [kJ/kgmole-C]	7.954
Heat Flow [kW]	-1.637
Liq Vol Flow @Std Cond [m3/h]	153.1
Fluid Package	Basis-1
Utility Type	

Figure 3.5: Simulation environment [8]

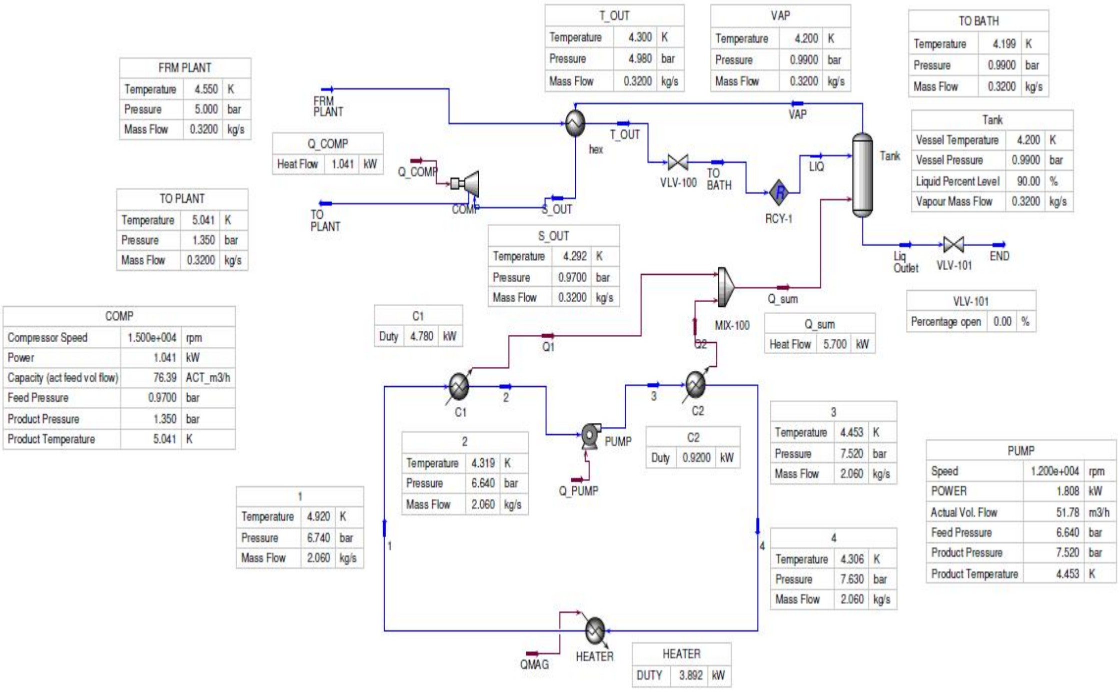
3.4 Steady-State Modeling

In the steady state modeling cryogenic components are modeled such as cold compressor, heat exchanger, separator, cooler, heater and pump. For the modeling the cryogenic system is divided into two loops: primary and secondary loop; In the secondary loop the LHe comes from the cryo plant and the vapor goes to the cold compressor and the primary loop is the one in which the heat load is taken from the magnet and dumped in the LHe bath/Separator.First in the secondary loop the cold compressor is modeled along with the worksheet of inlet, outlet streams from the cold compressor and its heat duty. Similarly, the heat exchanger and separator is modeled.[13]

It should be noted that in heat exchanger the exchanger design weighted is used because of the two phase flow in the heat exchanger and also of its advantages in the dynamic simulation.Whereas in the separator the outlet of the liquid stream is closed, it is so because the separator has to be simulated as LHe bath where only the helium vapor leaves the tank and not the liquid.

In the primary loop there are two coolers both are modeled in the same way and the specification of a cooler is . The magnet from where the heat load is taken by the super-critical Helium (SHe) and is dumped in the liquid helium bath using the energy streams of the two coolers which are connected by a mixer to separator/bath heat duty.

In same way as the compressor, the pump is also designed with an adiabatic efficiency of 70% and 0.88 bar pressure rise. Since the pressure rise is constant in the pump, it means that the power of the pump will be constant. After defining all the components and connecting all the streams we get a steady state model of the ITER cryogenic system. In the Fig. 3.6 a steady state model of a magnet is shown it doesn't look similar to the actual cryogenic system as shown in Fig. 2.5 but all the system considerations are met such as the heat load that is dumped inside the tank goes to the Separator and the vapor thus generated goes to the heat exchanger and then to the cold compressor and the LHe that comes from the cryo plant goes to the separator and hence its function is similar to the actual cryogenic system.



FRM PLANT		
Temperature	4.550	K
Pressure	5.000	bar
Mass Flow	0.3200	kg/s

TO PLANT		
Temperature	5.041	K
Pressure	1.350	bar
Mass Flow	0.3200	kg/s

COMP		
Compressor Speed	1.500e+004	rpm
Power	1.041	kW
Capacity (act feed vol flow)	76.39	ACT_m3/h
Feed Pressure	0.9700	bar
Product Pressure	1.350	bar
Product Temperature	5.041	K

Q_COMP		
Heat Flow	1.041	kW

T_OUT		
Temperature	4.300	K
Pressure	4.980	bar
Mass Flow	0.3200	kg/s

VAP		
Temperature	4.200	K
Pressure	0.9900	bar
Mass Flow	0.3200	kg/s

TO BATH		
Temperature	4.199	K
Pressure	0.9900	bar
Mass Flow	0.3200	kg/s

Tank		
Vessel Temperature	4.200	K
Vessel Pressure	0.9900	bar
Liquid Percent Level	90.00	%
Vapour Mass Flow	0.3200	kg/s

S_OUT		
Temperature	4.292	K
Pressure	0.9700	bar
Mass Flow	0.3200	kg/s

VLV-101		
Percentage open	0.00	%

C1		
Duty	4.780	kW

Q_sum		
Heat Flow	5.700	kW

C2		
Duty	0.9200	kW

1		
Temperature	4.920	K
Pressure	6.740	bar
Mass Flow	2.060	kg/s

2		
Temperature	4.319	K
Pressure	6.640	bar
Mass Flow	2.060	kg/s

3		
Temperature	4.453	K
Pressure	7.520	bar
Mass Flow	2.060	kg/s

4		
Temperature	4.306	K
Pressure	7.630	bar
Mass Flow	2.060	kg/s

PUMP		
Speed	1.200e+004	rpm
POWER	1.808	kW
Actual Vol. Flow	51.78	m3/h
Feed Pressure	6.640	bar
Product Pressure	7.520	bar
Product Temperature	4.453	K

HEATER		
DUTY	3.892	kW

Figure 3.6: Steady state model

Various estimated values of the unit operations and other equipments is in Table3.2. This table mainly describes the critical unit operations/equipments which is primarily used or modeled in the software. The heat exchanger which will be implemented in the ITER cryogenic system is mainly plate fin heat exchanger but due to the software restriction/availability of newer version it has been modeled as shell and tube heat exchanger. Similarly, the two heat exchangers are modeled as cooler. However, their main characteristics like pressure drop, temperature difference etc, are kept as realistic as possible. The Table 3.2 shows the various equipments used in steady state modeling and their exact or approximate estimated values that have been taken to model it.

Table 3.2: Steady State Equipments values

Equipments	Parameters	Estimated Values
Hex	Tube side pressure drop	2 kPa
	shell side pressure drop	2 kPa
	Overall heat transfer coefficient	2310 KJ/C-h
Compressor	Efficiency	70%
	Compressor Speed	15000 RPM
	Power	1.041 KW
Bath/Separator	Liquid percent level	90%
	Duty	5.7 KW
	Vessel Pressure/Temperature	0.99 bar / 4.2 K
	Volume	6 m^3
C1	Delta P	10 kPa
	Duty	4.78 KW
	Volume	0.10 $m3$
C2	Delta P	10 kPa
	Duty	0.92 KW
	Volume	0.10 m^3
PUMP	Delta P	88 kPa
	Efficiency	70 %
	Power	1.808 KW
	Speed	12000 RPM
HEATER	Duty	3.892 KW
	Delta P	89 kPa
	Volume	0 m^3
VLV-100	Valve Opening	100 %
	Delta P	400 kPa
	Cv (USGPM)	5.584
VLV-101	Valve Opening	0 %
	Delta P	0 kPa
	Mass flow	0 Kg/sec

Chapter 4

Dynamic Simulation of Thermal Systems

The contrast between element models and unfaltering state models is that a dynamic model illuminates the numerical offsets for individual properties, for example, vitality, material and synthesis as a component of time. This is finished by including a period subordinate "accumulation"term in these separate transport mathematical statements and separating over the long haul. The approximated arrangement is acquired by numerical incorporation, as the time-subordinate mathematical statements are non-straight in nature and along these lines systematic arrangements are elusive. HYSYS tackles most unit operations by utilizing lumped models, implying that directional slopes (along the x,y and z tomahawks) are dismissed and the explained property is thought to be steady inside every sub-volume. The dynamic conduct of procedure hardware is in view of the way that they frequently have a burglary volume, bringing about a period postpone between when changes are presented at its channel and when these are seen at its outlet. HYSYS Dynamics-TM models the transient framework conduct in particular procedure hardware by utilizing individual robbery models, considering their distinctive appearances and usefulness. As the postponement accordingly of a property when changes are presented is an aftereffect of collection, understanding the aggregation term is the way to reenact the reaction. For this, the burglary model includes a hypothetical reuse stream close by the food stream which basically speaks to the material effectively existing inside the equipment.The collection is then fathomed by: [6][16][17]

Accumulation = Flow into system + Recycle stream - Flow out of system

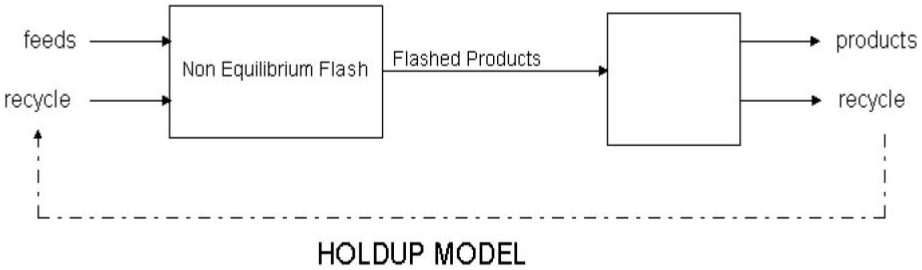


Figure 4.1: Holdup Model [6]

The presumptions made in the HYSYS robbery model are:

- Each stage is thought to be very much blended.

- Mass and warmth exchange happen between nourishes to the robbery and material as of now in the burglary.
- Mass and warmth exchange happen between stages in the burglary.

Albeit every stage is expected consummately blended all alone, this does exclude the multiphase blending between the food channel and the current robbery (reuse stream) if a few physical stages are available. Case in point, the blending and equilibration of two different fluid vapor streams is exceedingly reliant on the inward geometry and living arrangement time of the hardware. The blending efficiencies representing the multiphase blending of the burglary volume can be indicated in HYSYS and hence the time required for the robbery volume to achieve balance can be adjusted. In the event that the blending efficiencies are situated low, the framework may not have room schedule-wise to achieve balance and the item stream can for instance contain stages with diverse temperatures. Weight in diverse unit operations and channeling is in HYSYS illuminated by utilizing resistance comparisons of the form:

$$F = K\sqrt{\triangle P}$$

Here the mass stream rate is portrayed as an element of a particular resistance parameter (k) and weight drop (delta P) from contact for a particular unit operation. For a valve, the resistance is displayed by the Cv esteem. The Valve unit operation is demonstrated in HYSYS as two unique components: an actuator and a valve. A few choices alongside Cv are accessible for the actuator and valve, for example, opening time and valve stickiness. Vast pivoting parts in for instance compressors are applied to powers due idleness and grinding. The impact of quickening a compressor impeller is critical for element simulations and can be demonstrated by determining inactivity and related parameters in the HYSYS model for the compressor unit operation.

In the following sub sections I have simulated loops separately so that to get an idea of the working of dynamic simulation briefly in the first case I have simulated the lower loop with magnets and cooler and then the upper loop with separator and valves.

4.1 Rules for Dynamic Simulation

In the dynamic simulation the unit operation and streams have to be defined separately for the dynamic simulation[7][14][15]. There are ten basic rules for dynamic simulation :

1. Every boundary stream (feed or product stream) should have one dynamic spec: In real life there are no boundary streams. Every stream has to come from or go to some where. The sources of these feed streams or the destinations of product streams can be approximated using specs on the boundary streams. For example a pressure spec on a feed stream can approximate a draw from a big pipeline, where the draw amount will not affect the pressure inside the pipe. It can also approximate suction of air directly from atmosphere, where the pressure will not

change regardless of how much flow you draw. The integrator uses this spec to then calculate the rest of the flows and pressures for the model based on the sizes and resistances of operations.

2. Never use Flow specs on streams: Flow specs are not realistic. Usually you get flow as a result of a pressure difference and some size. For example, if you use a flow spec on the inlet of a separator, and the separator outlets were closed, the pressure in the separator will rise until the solver fails. Whereas if you use a pressure spec (and a valve) the pressure in the vessel can only rise till it reaches the feed stream pressure, which is more realistic.

3. Never use dynamic specs on streams within the flow sheet: Contrary to Steady State simulation, all the streams within a flow sheet should be left with no dynamic specs at all. Fixing a pressure or a flow in any of these streams will force a behavior other than what operation sizes and pressure profile dictates and hence skews the transient trends of the model.

4. All boundary streams must be connected to resistance operations: Resistance operations are those which have a Pressure/Flow relation (i.e. they can calculate a flow from a pressure drop and a size and vice versa). For example: valves, heat transfer operations (except re boilers and condensers in column sub flow sheets), plug-flow reactors and rotating equipment.

5. Never connect two pressure node operations together without a resistance operation in-between: Pressure nodes are the holdup operations like separators, tanks, reactors (other than PFR) and columns (feeds and side draws only). These operations can't calculate a flow for their connected feed or product streams. They only use volume balance and accumulation equations to calculate a holdup amount. So make sure all your feeds to these operations or products from them go through a resistance operation.

6. No dynamic model runs properly without controllers: In steady state models you have specs; in dynamics you have controllers. There is no way you can just ignore the controllers. They are as essential to your dynamic model as they are to a real plant.

7. No dynamic model is useful without strip charts: Dynamic modeling is all about trends and changes over time. Only a strip chart can show you this relation. Never rely on reading a number off a view as it can change the next second. Strip charts will show you disturbances, oscillations, instabilities and controller behavior.

8. Duty streams are not realistic in Heat Transfer equipment: Try to minimize the use of duty streams to represent heating and cooling in your model. Heat exchangers, air coolers, fired heaters and two sided vessels (like re boilers) are the best way to model heat transfer equipment. Duty streams can always be tricked to over heat or over cool, which results in model instability and solver failures.

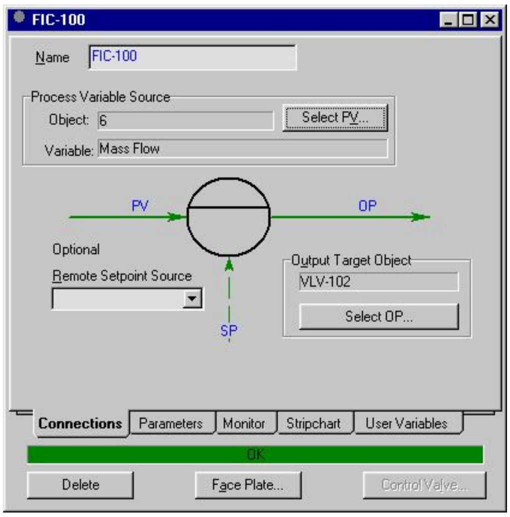
9. All columns must have sumps: In HYSYS columns end with a tray and not a sump. In real life columns end with a sump and not a tray. So always make sure your column ends with a sump by either adding a separator to the bottom of the column, or adding a tray of type sump

(HYSYS 3.2 and later only). Sumps allow you to model the level control at the bottom of the column, and ensure proper pressure driven flow.

10. Be careful with pumps and duty specs: Duty specs on pumps can only be used if a recycle and pressure control to protect the pump are modeled. Otherwise use a pressure rise spec.

4.2 PID Controller

The Controller operation is the essential method for controlling the model in Dynamic mode. It conforms a stream (OP) to keep up a particular stream sheet variable (PV) at a certain magnitude (SP).The PID Controller is shown in Fig. 4.2.



FIC-100

Name: FIC-100

Process Variable Source

Object: 6

Variable: Mass Flow

Output Target Object: VLV-102

Figure 4.2: PID Controller [8]

To connect the Process Variable Source, tap the Select PV catch. At that point select the suitable question and variable at the same time, utilizing the Variable Navigator.The Variable Navigator property perspective permits you to all the while select the Object and Variable.

The Output of the Controller is the control valve which the Controller controls keeping in mind the end goal to achieve the set point. The yield sign, or OP, is the fancied percent opening of the control valve, taking into account the working reach which you characterize in the Control Valve property view.Selecting the Output Target Object is done in a comparable way to selecting the Process Variable Source. You are likewise constrained to protests bolstered by the controller and not right now connected to another controller.

The PV (or Process Variable) is the deliberate variable, which the controller is attempting to keep at the Set point. The SP (or Set point) is the estimation of the Process Variable, which the Controller is attempting to meet. Contingent upon the Mode of the Controller, the SP is either entered by the client or showed just.

For the Controller to wind up operational, you should:

1. Characterize the base and greatest qualities for the PV (the Controller can't change from Off mode unless PV min and PV max are characterized).

2. When you give these qualities (and also the Control Valve compass), you may choose the Automatic mode, and give a quality for the Set point. [11]

The governing equation of a PID controller is :

$$OP = (Kc * e) + \frac{1}{Ti} * (\int e.dt) + Td * (\frac{de}{dt})$$

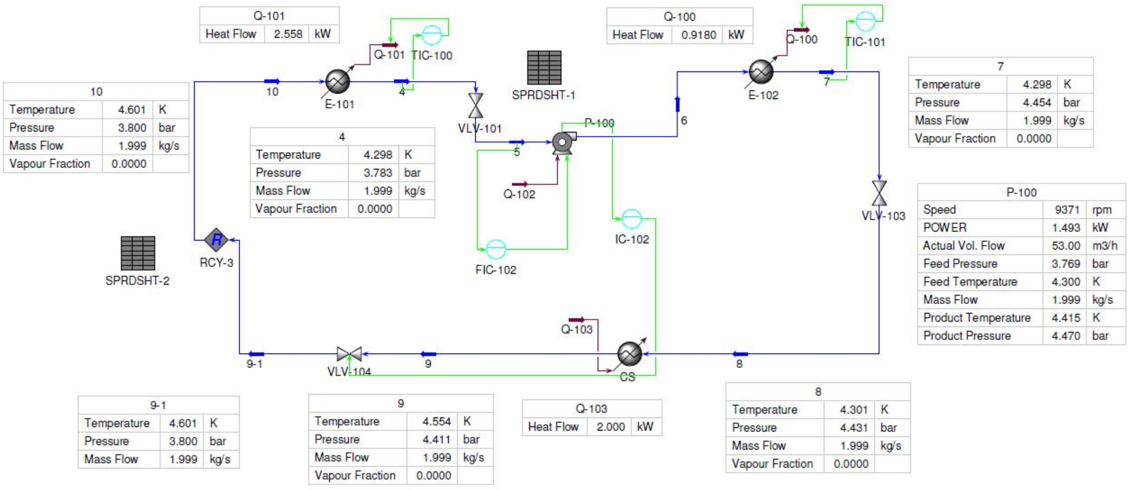
Where, e = PV - SP,

and Kc, Ti and Td are the gain parameters which have to be given as an input for different pressure, temperature, mass flow or liquid percent level controllers. Different controllers will require different values of gain parameters depending upon its use in the loop.

4.3 Dynamic Simulation of Primary Loop

The dynamic simulation of primary loop consist of a magnet with variable heat load w.r.t time and two heat exchangers which are simulated as cooler's and a cold circulator pump to overcome the pressure drop in the loop. The medium used for the cooling of superconducting magnets is supercritical helium (SHe) as also explained in the [19] in place of sub-critical helium. A modeled primary loop is shown in Fig. 4.3whose configuration is similar for all the magnets (CS, TF, ST & PF) primary loop.

The primary loop was simulated and was kept as realistic as possible, for example the mass flow in the primary loop of CS magnet is 2 kg/sec and a pressure drop of 70 kPa as in the original configuration. Similarly, it was done for other magnets primary loop. The cold circulator pump was dynamically simulated with characteristics curve at 12000 RPM as given from the industry. The cold circulator pump is simulated to work at a constant pressure rise and hence the power remains constant for most of the simulation duration.



Q-101		
Heat Flow	2.558	kW

10		
Temperature	4.601	K
Pressure	3.800	bar
Mass Flow	1.999	kg/s
Vapour Fraction	0.0000	

4		
Temperature	4.298	K
Pressure	3.783	bar
Mass Flow	1.999	kg/s
Vapour Fraction	0.0000	

Q-100		
Heat Flow	0.9180	kW

7		
Temperature	4.298	K
Pressure	4.454	bar
Mass Flow	1.999	kg/s
Vapour Fraction	0.0000	

P-100		
Speed	9371	rpm
POWER	1.493	kW
Actual Vol. Flow	53.00	m3/h
Feed Pressure	3.769	bar
Feed Temperature	4.300	K
Mass Flow	1.999	kg/s
Product Temperature	4.415	K
Product Pressure	4.470	bar

9-1		
Temperature	4.601	K
Pressure	3.800	bar
Mass Flow	1.999	kg/s

9		
Temperature	4.554	K
Pressure	4.411	bar
Mass Flow	1.999	kg/s
Vapour Fraction	0.0000	

Q-103		
Heat Flow	2.000	kW

8		
Temperature	4.301	K
Pressure	4.431	bar
Mass Flow	1.999	kg/s
Vapour Fraction	0.0000	

Figure 4.3: Primary Loop

Various parameters of the equipments in the primary loop is shown in table 4.1.

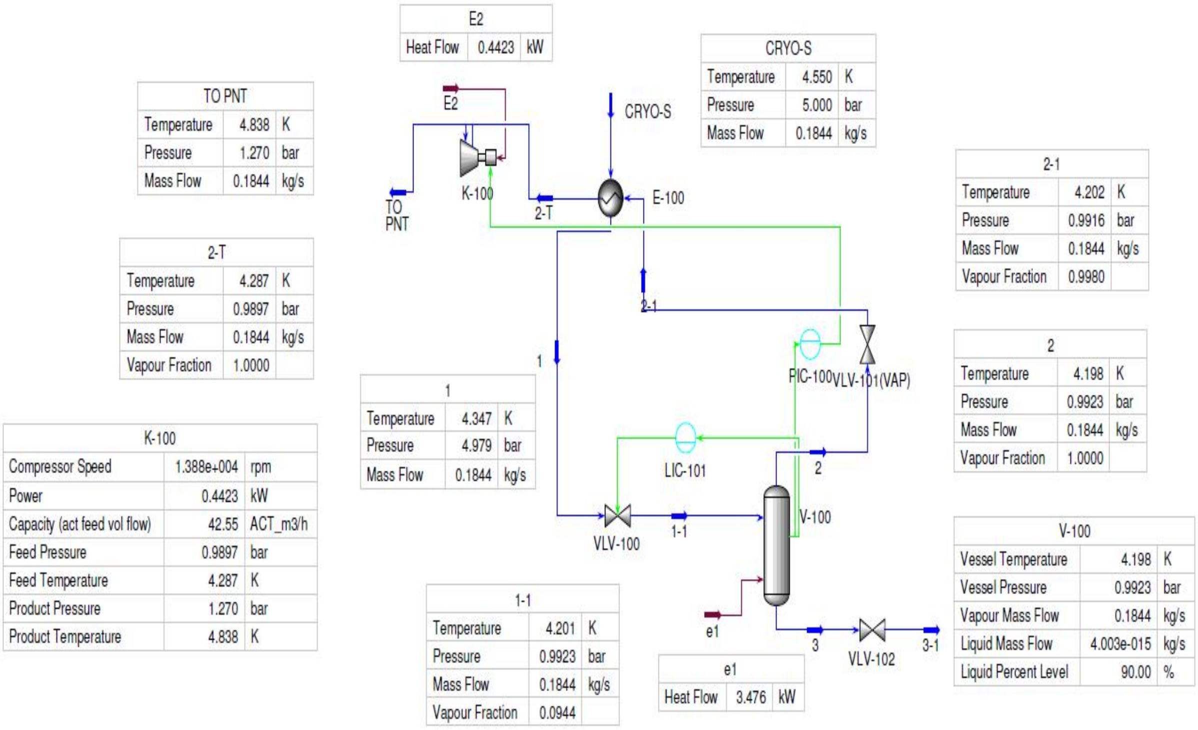
Table 4.1: Primary Loop

Equipment	Parameters	Estimated Values
CS	Overall K	430 Kg/hr/sqrt(kPa-kg/m^3)
	Volume	0 m^3
E-101	Overall K	480 Kg/hr/sqrt(KPa-Kg/m^3)
	Volume	5 m^3
E-102	Overall K	480 Kg/hr/sqrt(KPa-Kg/m^3)
	Volume	2.5 m^3
VLV-101	Valve opening	100%
	Cv(USGPM)	195.7
	Delta P	1.332 kPa
	Mass Flow	2 Kg/sec
VLV-103	Valve opening	100%
	Cv(USGPM)	148.6
	Delta P	2.276 kPa
	Mass Flow	2 Kg/sec
VLV-104	Valve opening	57.83 %
	Cv(USGPM)	150.4
	Delta P	61 kPa
	Mass Flow	2 Kg/sec
SPREADSHEET 1	Import	E-101 & E-102 (Duty)
	Export	e1 (Heat Flow)
SPREADSHEET 2	Import	V-100 (Vessel Temperature)
	Export	TIC-100 & TIC-101 (SP)
TIC-100	PV	Stream-4 (Temperature)
	OP	Q-101 (Heat Duty)
	SP	4.298 K
TIC-101	PV	Stream-7 (Temperature)
	OP	Q-100 (Heat Duty)
	SP	4.298 K
FIC-102	PV	Stream-5 (Mass Flow)
	OP	P-100 (Speed)
	SP	2 Kg/sec
IC-102	PV	P-100 (Delta P)
	OP	VLV-104 (Actuator Desired Position)
	SP	70 kPa

4.4 Dynamic Simulation of Secondary Loop

The dynamic simulation of secondary loop consists of LHe bath modeled as Separator a heat exchanger which is modeled as shell and tube counter flow weighted heat exchanger, it is used because of the two phase flow that will pass through the heat exchanger. A cold compressor is connected with the heat exchanger which compresses the already heated vapor from heat exchanger and sends back it to the cryo plant. The incoming Liquid helium from the cryo plant gets pre cooled in the heat exchanger and is then expanded isenthalpically through a joule-thompson (J-T) valve and as a result the liquid helium gets stored in the bath/separator. The secondary loop is shown in Fig. 4.4.

The secondary loop was also kept as realistic as possible, for example the LHe bath was at constant pressure 0.9923 bar using a PID controller and the cold compressor characteristic curves for different configuration were thoroughly simulated. The volume of the vessel/bath was kept 6 m^3,whereas the volume of magnet/heater was kept 0 m^3because it was observed when the transient heat load was given using event scheduler the heat load profile was not consistent with time and resulting in ambiguous heat load profile for heater as well as two HEX/cooler's. The HX-1 volume was kept 5 m^3 and HX-2 at 2.5 m^3 this is because maximum amount of heat load(mainly magnet heat load) will be taken up by the HX-1, whereas small heat load in the range of 1 - 2 kW will be disposed by HX-2 and hence its volume is kept small.



E2		
Heat Flow	0.4423	kW

CRYO-S		
Temperature	4.550	K
Pressure	5.000	bar
Mass Flow	0.1844	kg/s

TO PNT		
Temperature	4.838	K
Pressure	1.270	bar
Mass Flow	0.1844	kg/s

2-1		
Temperature	4.202	K
Pressure	0.9916	bar
Mass Flow	0.1844	kg/s
Vapour Fraction	0.9980	

2-T		
Temperature	4.287	K
Pressure	0.9897	bar
Mass Flow	0.1844	kg/s
Vapour Fraction	1.0000	

2		
Temperature	4.198	K
Pressure	0.9923	bar
Mass Flow	0.1844	kg/s
Vapour Fraction	1.0000	

1		
Temperature	4.347	K
Pressure	4.979	bar
Mass Flow	0.1844	kg/s

K-100		
Compressor Speed	1.388e+004	rpm
Power	0.4423	kW
Capacity (act feed vol flow)	42.55	ACT_m3/h
Feed Pressure	0.9897	bar
Feed Temperature	4.287	K
Product Pressure	1.270	bar
Product Temperature	4.838	K

V-100		
Vessel Temperature	4.198	K
Vessel Pressure	0.9923	bar
Vapour Mass Flow	0.1844	kg/s
Liquid Mass Flow	4.003e-015	kg/s
Liquid Percent Level	90.00	%

1-1		
Temperature	4.201	K
Pressure	0.9923	bar
Mass Flow	0.1844	kg/s
Vapour Fraction	0.0944	

e1		
Heat Flow	3.476	kW

Figure 4.4: Secondary Loop

Various estimated values of equipments like compressor (K-100) speed, efficiency and outlet pressure, vessel/bath (V-100) volume, liquid percent level and various other parameters of heat exchanger, valve's and PID controller mainly liquid percent level controller and pressure controller are shown in the table 4.2.

Table 4.2: Secondary Loop

Equipments	Parameters	Estimated Values
K-100	Speed	15000 RPM
	Efficiency	70 %
	Outlet Pressure	1.27 bar
V-100	Volume	6 m^3
	Liquid Percent Level	90 %
E-100	Shell Side Delta P	2 kPa
	Tube Side Delta P	2 kPa
	Overall heat transfer (UA)	2906 kJ/C-h
VLV-100	Percentage open	100 %
	Delta P	0.1 kPa
	Cv (USGPM)	14.09
VLV-101 (VAP)	Percentage open	100 %
	Delta P	0.1 kPa
	Cv (USGPM)	778.3
VLV-102	Percentage open	0 %
	Delta P	0 kPa
	Cv (USGPM)	0
LIC-101	PV	V-100 (Liquid percent level)
	OP	VLV-100 (Actuator desired position)
	SP	90 %
PIC-100	PV	V-100 (Vessel Pressure)
	OP	K-100 (Speed)
	SP	0.9923 bar

Cold compressor characteristic curve values were derived from the given mass flow and head values. where the inlet pressure, temperature, efficiency and speed values are given from the industry.

4.5 Dynamic Simulation of Common CCB & PF Magnet

The dynamic simulation of the common cold compressor box (CCB) with individual bath/vessel for CS, TF and ST magnet and PF magnet with its own cold compressor was performed. The results obtained are discussed in chapter 5 and the configuration of the CCB & PF is shown in Fig. 4.5 the estimated values entered will be the same for primary loop and secondary loop for all the magnets as shown in table 4.1 and 4.2. The only change in the secondary loop is the removal of individual cold compressor except the PF magnet and in the place of three cold compressor only one is used.

As can be seen in the 4.5 the liquid helium coming from the plant is split in two streams using a TEE, one of the stream goes to the PF magnet and then to its heat exchanger where it is pre-cooled before the expansion through J-T valve. The second stream goes to the heat exchanger shell side which is common for all the three magnets and in the outlet is again split into three streams to be given as the feed stream of the J-T valve for expansion in magnets individual vessel/bath. The outlet of the two cold compressor is mixed using a MIXER and the resultant goes to the cryo plant.

Suitable characteristic curve were given as an input at different speed of 4620, 4980 and 5520 rpm, with these curves the cold compressor could handle mass flow ranging from 1200 - 3200 g/s. and as the result shows the maximum liquid/vapor helium to/from the cryo plant is not above 2250 g/s. Hence, it can be assured that the compressor does not choke at peak conditions. The average efficiency was 79.5 % and suction pressure/temperature at 0.97 bar/4.3 K. Similarly, for the PF magnet the characteristic curve were given as an input at 13320, 13800 and 14040 rpm with inlet pressure and temperature of 0.99 bar and 4.3 K respectively. The average efficiency was kept at 71.9 %. The cold compressor has such high rpm because of the mass flow which is very less at around 240 - 440 g/s.

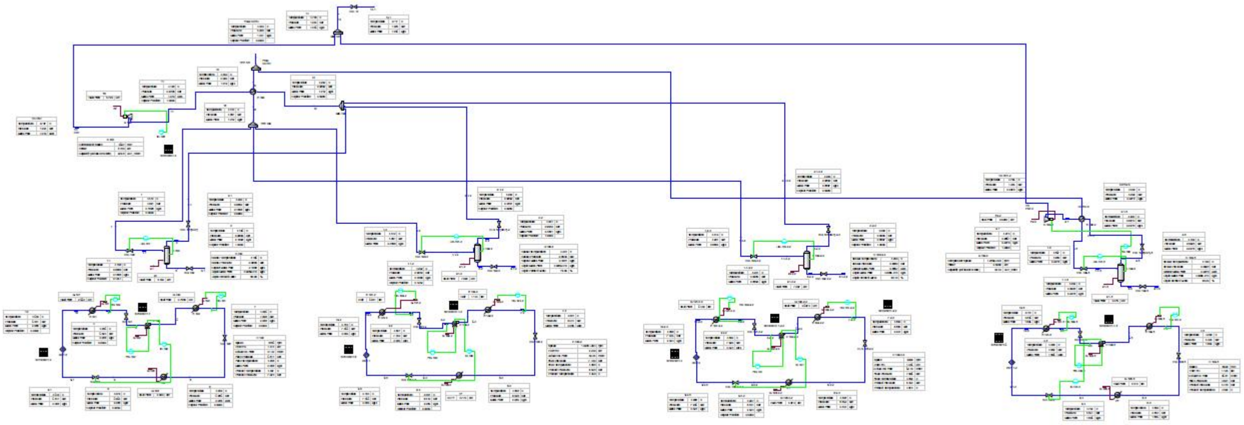


Figure 4.5: CCB & PF Magnet

4.6 Dynamic Simulation of Individual CCB for Magnets

The dynamic simulation for the individual cold compressor box (CCB) with individual bath for magnets is similar to the common CCB. The only difference is that each magnet has its own cold compressor as well as a heat exchanger. The outlet of each CCB is united using a MIXER and is sent to the cryo plant. Whereas the inlet from the cryo plant is separated using a TEE. The primary and secondary loop equipments/unit operations will have the same configuration as described in table 4.1 and 4.2 respectively. The results thus obtained are discussed in chapter 5. The configuration of individual CCB is shown in Fig. 4.6.

The characteristic curves for CS, TF and ST magnets were completely different and at various speed of 15000 - 30000 rpm, CS and TF magnets were given characteristics curve from 15000 - 17000 rpm whereas the ST magnet had a range of 15000 - 30000 rpm due to the high heat load profile of its magnet but still its cold compressor speed was remaining constant at peak heat loads, it shows that different characteristic curve should be used for the magnet at higher speed and with a high pressure head as the mass flow rate range for all the cold compressor is 300 - 900 g/s. The PF magnet was provided the same characteristics curve as explained in the above point.

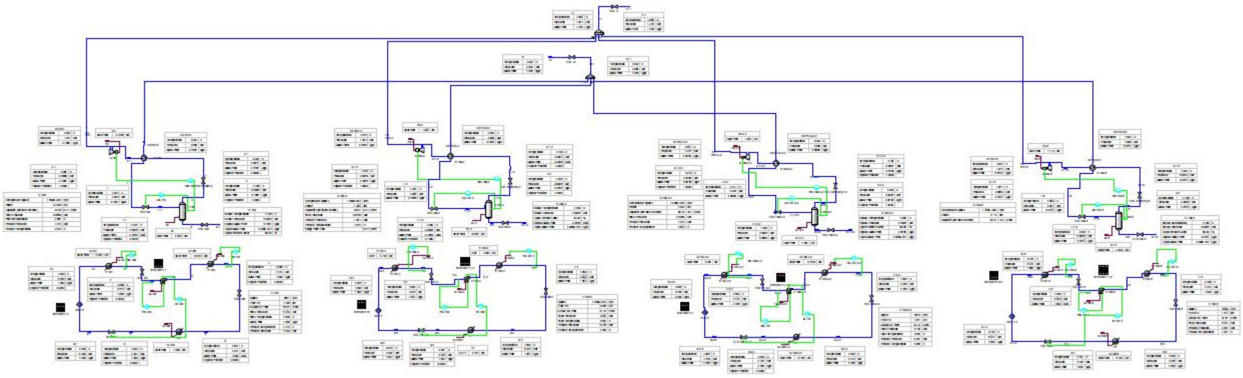


Figure 4.6: Individual CCB

4.7 Dynamic Simulation of Common Liquid Helium Bath with Common CCB for Magnets

In this simulation the secondary loop of CS, TF and ST magnets were removed and in its place only one cold compressor and liquid helium bath/vessel was used, the configuration of PF magnet was kept as it is. The mass flow coming out from the common LHe bath and the PF bath are joined together using a mixer and is then sent to the cryo plant. Whereas, the inlet from the cryo plant is sent to the respective bath using a separator tee. A graphic customization of this configuration is shown in Fig. 4.7. The results of this simulation is explained in chapter 5. Common cold compressor was given the same characteristic curve as the common cold compressor with individual bath, the common liquid helium bath volume was changed to 20 m^3 as it acts as the only source for magnets to dump their heat load. There is only one secondary loop for three magnets (CS, TF and ST) whereas, the PF magnet has its own primary and secondary loop.

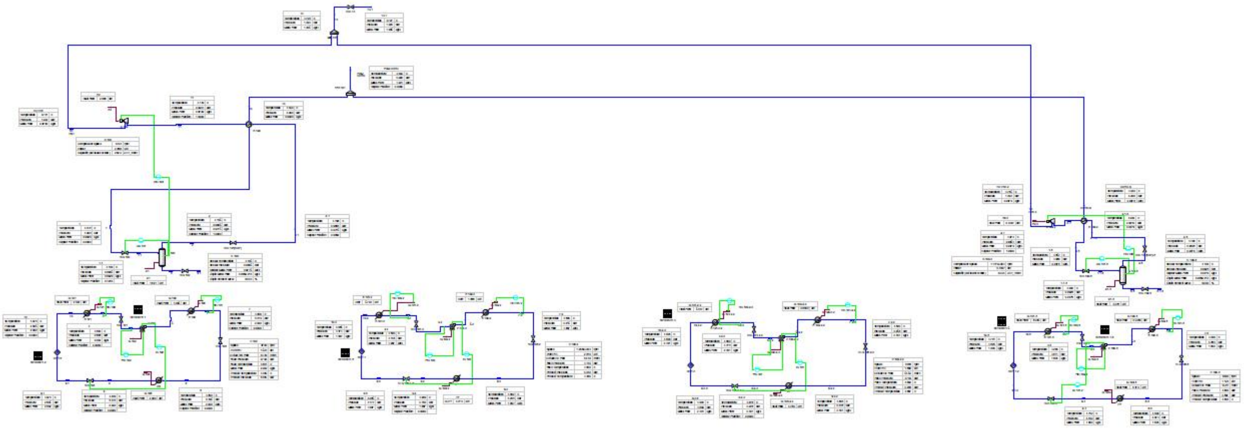


Figure 4.7: Common Liquid helium bath

Chapter 5

Results and Discussions

The results of steady state simulation and dynamic state simulation for different configurations are explained in this Chapter.

5.1 Steady State Simulation

From the steady state simulation, it was observed that although the configuration of the steady state model was different from the analytical system configuration, the properties obtained were similar to the analytical system. The table shown in 5.1 compares the steady state model values with the analytical values calculated using HEPAK.

Table 5.1: Comparison of steady state with actual system

Unit operation	Property	Software Calculated Values	Analytical Values Calculated using HEPAK
Heat Exchanger	Temperature (Tube inlet)	4.55 K	4.55 K
	Temperature (Tube outlet)	4.30 K	4.30 K
	Temperature (Shell inlet)	4.20 K	4.20 K
	Temperature (Shell outlet)	4.292 K	4.29 K
Compressor	Temperature (inlet)	4.292 K	4.29 K
	Temperature (outlet)	5.041 K	5.03 K
Separator / Bath	Temperature (Vapor)	4.2 K	4.2 K
	Heat duty	5.7 kW	5.7 kW
Cooler/Heat Exchanger (1)	Heat duty	4.78 kW	4.78 kW
Cooler/Heat Exchanger (2)	Heat duty	0.92 kW	0.92 kW
Pump	Temperature (inlet)	4.31K	4.3K
	Temperature (outlet)	4.547K	4.54K
	Pressure rise	0.88 bar	0.88 bar
	Heat duty/power	1.818 kW	1.80 kW

It can be observed from the Table 5.1 that the values calculated by the software steady state simulation is in close agreement with the analytical values calculated by HEPAK, which can be neglected as it will not have any major impact on the system. Hence, the system modeled above is near to accurate and can be used for further dynamic simulation.

5.2 Dynamic State Simulation

In dynamic simulation, the systems was modeled correctly with different configuration as discussed in the Chapter 4, section 4.5 - 4.7. For e.g. the LHe bath should maintain fluctuation in the range of 80% - 90% of liquid helium and the rest of the vapor should go to the cold compressor as there always has to be some mass flow rate in the vapor line of the LHe bath which was also simulated accurately using the PID controller. The primary loop of the dynamic state model was also simulated which contained two coolers, one magnet/heater and a pump. The loop was simulated perfectly and the desired results were met and different configuration simulation was carried out.

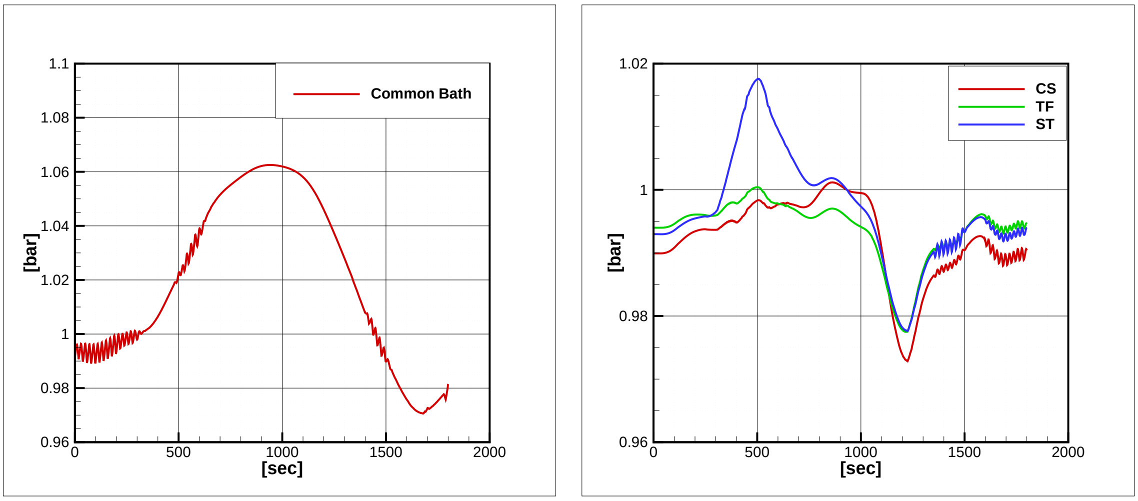
In the following sections, various results obtained from the simulation of common LHe bath with common cold compressor; Common cold compressor with individual bath and individual cold compressor with individual liquid helium bath have been explained in detail. The three important parameters to be discussed are : liquid helium bath pressure variation, level variation and mass flow to/from the cryo plant. The simulation results snapshot can be seen and matched in Appendix A.

5.2.1 Liquid helium bath pressure variation (for CS, TF and ST)

The liquid helium bath pressure variation for common LHe bath pressure increases because the sum of heat load by the three magnets is dumped in a single bath/vessel and as a result high pressure fluctuation can be observed in Fig. 5.1a as the common heat load profile is similar to the vessel pressure fluctuation.

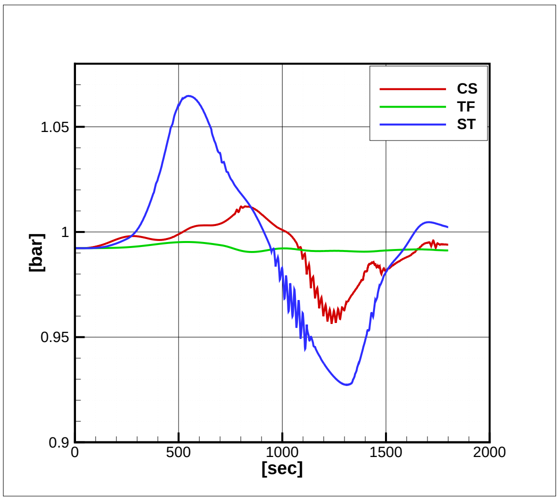
For common cold compressor, the pressure variation is different for each magnet liquid helium bath, due to the PID controller which keeps the vessel pressure above or below the set point of 0.9923 bar such that the average of these three pressure matches the set point of PID controller. The ST magnet vessel pressure sees a sudden spike at around 500 - 600 seconds because the peak heat load of ST magnet reaches early during that time period and correspondingly the vessel pressure increases. The TF magnet has a moderate heat load profile between 5 - 7 kW and hence it is near to the set point of the controller as can be seen in Fig. 5.1b. The sudden drop in the vessel/bath pressure at around 1100-1200 seconds is due to the combined heat load which drops steeply after this time frame.

In the individual cold compressor and individual bath, the CS magnet has a peaking heat load till 900 seconds and decreases rapidly thereafter and hence the pressure drop in vessel can be seen near about 1000 seconds,TF magnet has a moderate heat load variation between 5-7 kW and does not cause much vessel/bath pressure fluctuation and remains close to the set point of its PID controller. The ST magnet peaks around 500 seconds and hence the bath pressure fluctuation above the set point, and the sudden drop after 1000 seconds can be attributed to its controller, the vessel pressure graph is shown in Fig. 5.1c. The three graphs are shown in Fig. 5.1.



(a) Common LHe bath

(b) Common Cold Compressor



(c) Individual Cold Compressor

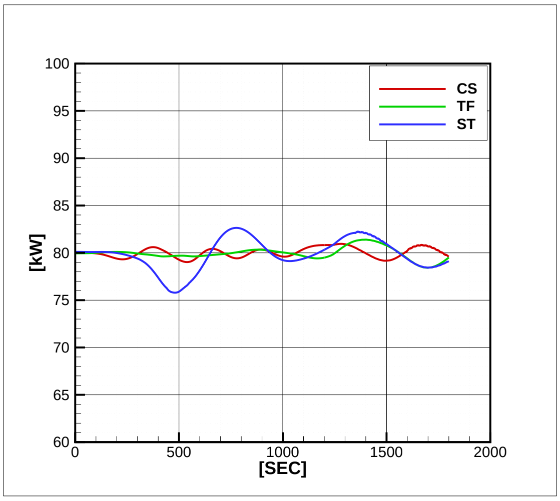
Figure 5.1: LHe bath pressure variation

5.2.2 Liquid Helium Level Variation (for CS, TF and ST)

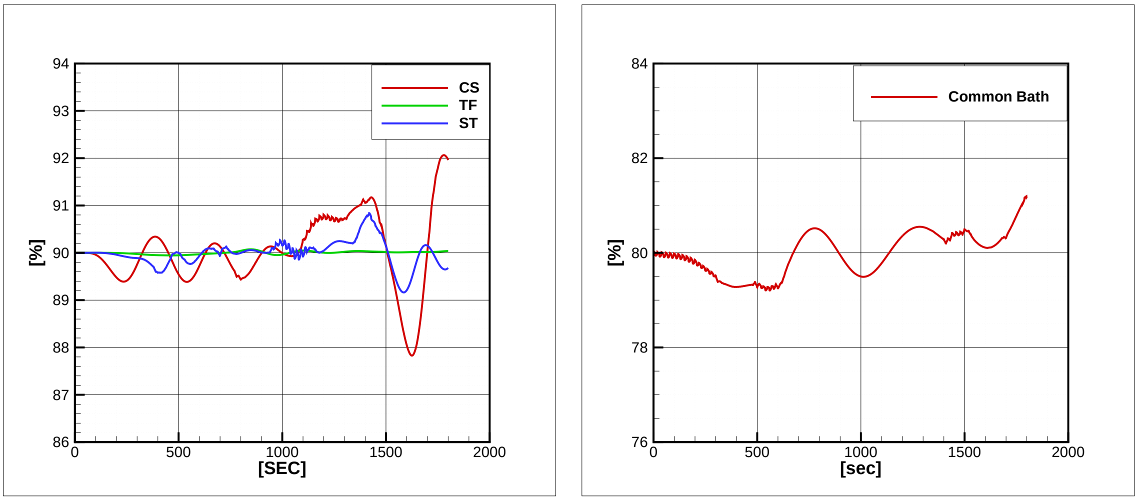
The liquid percent level for the common cold compressor with individual liquid helium bath magnet is kept at 80 %. The variation of TF and CS are satisfactory whereas, there is some fluctuation in the ST magnet at around 500 seconds, this is due to the ST magnet heat load profile peaks at around 400 – 600 seconds and decreases gradually. The rest of the disturbance can be due to the tuning parameters of the ST magnet Liquid level controller, the graph is shown in Fig.5.2a.

For individual cold compressor and LHe bath, TF and ST variation is in the range of $\pm 1\%$ from the set point neglecting the high variation at the end of the simulation time, the percent level of each magnet remains at satisfactory percentage and cannot cause any trouble/damage to the secondary loop during the actual running. The graph is shown in Fig. 5.2b.

In the common liquid helium bath, vessel pressure fluctuation occurs at every second as the heat load from the three magnets is dumped into a single bath and it is important that the vessel liquid percent level is kept at certain limit and for this a PID controller is placed which controls the J-T valve so as to keep the vessel liquid percentage level at a certain level, the vessel's liquid percentage variation can be seen in Fig. 5.2c. The vessel liquid percentage level is near about ±1% as the vessel pressure observed in Fig. 5.1a increases and decreases gradually and hence gives the PID controller sufficient time to control the bath liquid level percentage.



(a) Liquid Percent Level: Common CCB and Individual LHe bath



(b) Liquid Percent Level: Individual Compressor and Individual LHe bath

(c) Liquid Percent Level: Common LHe bath and Common CCB

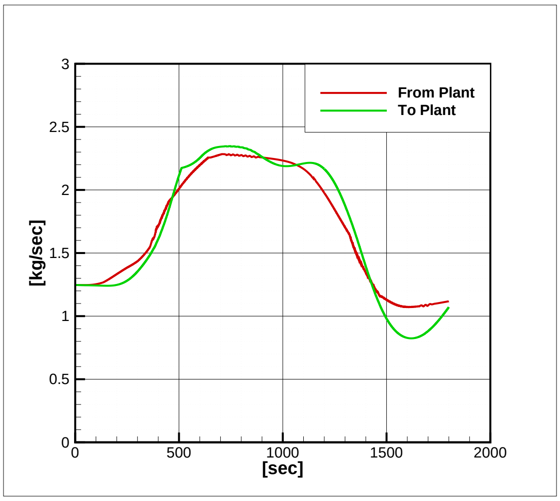
Figure 5.2: Liquid Percent level

5.2.3 Mass Flow IN/OUT of the Cryo Plant

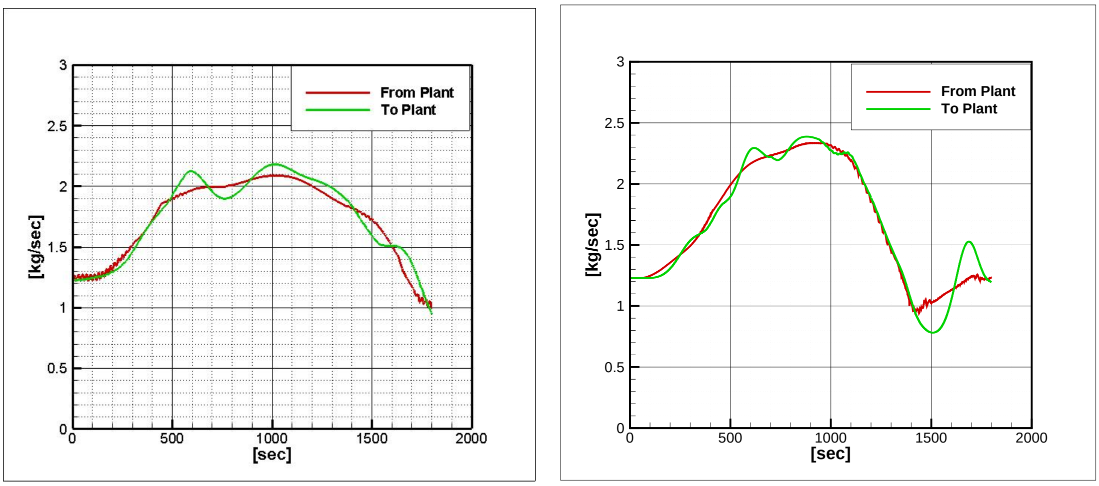
The common cold compressor and individual bath mass flow rate IN (from the Cryo plant) should be similar to the mass flow rate OUT (to the plant) as the vapor generated inside the vessel/bath and the vapor generated due to the J-T effect goes to the Cryo plant and thus the deficiency of LHe is compensated by the LHe sourced from the Cryo plant. The profile thus seen in the Fig 5.3a is almost similar and the slight change in the mass flow "To Plant" at peak condition can be attributed to the gain parameters of Liquid percent level of vessel/bath controller, the graph can be observed in Fig. 5.3a.

In common cold compressor and common liquid helium bath there is difference between the mass flow rate to/from the cryo plant this is because of the net heat load from the three magnets which is dumped in a single bath causes the vessel pressure to increase substantially and thus the vapor mass flow(to the cryo plant) increases. In order to compensate this decrease in liquid level the controller adjusts the J-T valve to increase the bath liquid level. Since, the bath level and vessel pressure(which indirectly control vapor/return mass flow) are controlled by different PID controllers hence, there is certain difference in their profile as can be observed in Fig. 5.3b.

As expected in the individual cold compressor and individual bath, the mass flow in and the mass flow out should have similar profile throughout the simulation. The fluctuation in the mass flow from the plant can be attributed to; the heat load profile of the magnet. All the four magnets heat load may either increase or decrease at a particular instant and the level controller of their respective vessel/bath may sometime not allow the liquid from Cryo plant to enter as the set point is already achieved. Whereas, the pressure inside the vessel/bath continues to increase/decrease and thus sending more mass flow to the Cryo plant and hence the difference in their profile, as shown in Fig. 5.3c



(a) Common Cold Compressor and Individual Bath: Mass Flow rate



(b) Common Cold Compressor and Common Bath: Mass Flow rate

(c) Individual Cold Compressor and Individual Bath: Mass Flow rate

Figure 5.3: Mass Flow In/Out

5.3 Summary of Chapter

1. The dynamic simulation of primary loop and secondary loop was done and was simulated in various other configuration.
2. The dynamic simulation of common cold compressor with individual liquid helium bath for CS,TF and ST magnet with a PF magnet was successfully done, to achieve the required the vessel/bath pressure for each magnet using the common cold compressor.
3. The dynamic simulation of Individual cold compressor with individual bath for CS,TF, ST and PF magnet was successfully done and various profile like bath pressure, bath fluctuation and mass flow rate to/from the plant was observed and discussed in detail.
4. The dynamic simulation of common liquid helium bath with common cold compressor for CS, TF and ST magnet with a PF magnet was successfully done and its effect on bath pressure, bath fluctuation and mass flow rate to/from the plant was realized on the system.
5. The results obtained from the three simulation were observed for different parameters like bath level fluctuation, bath pressure and mass flow IN/OUT of the cryo plant.

Chapter 6

Conclusions and Future Work

The conclusions and future work drawn from the present study are as following:

6.1 Conclusions

- The steady state simulation was done using ASPEN HYSYS 7.1 with the properties of unit operations matching that of analytical system as calculated by HEPAK for liquid helium cryogenic system at a heat load of 2 kW.
- The simulation study performed for the three configuration using ASPEN HYSYS 7.1 and different results were analyzed :

1. The heat load profile of HX1 and HX2 magnets for CS, TF, ST and PF magnets was almost similar to the heat load profile of their respective magnets and the heat duty profile of HX2 is almost constant as it takes up heat produced by the cold circulator pump which runs at a constant speed and hence produces constant power.
2. The simulation of vessel pressure, vessel bath level fluctuation and mass flow rate IN/OUT of the cryo plant; results were discussed in the previous chapter, and their behavior w.r.t the heat load profile of the magnet and tuning of gain parameters were performed.
3. The compressor speed variation for magnets was analyzed and it was observed that the compressor speed increases with the heat load and due to which the vessel pressure increases, so to keep the vessel pressure at specified value it increases its speed and hence the profile of compressor speed is realized.
4. One of the requirement of HX1 and HX2 cooler outlet temperature was to be kept 0.1 K greater than vessel/bath temperature, which was accomplished by changing the set point of the PID controller w.r.t the vessel/bath temperature. The results obtained from the simulations were satisfactory.

6.2 Future Work

- The secondary loop should be extended and should include the liquid helium plant assembly as it will be connected to the plant in real scenario.
- The heat exchanger modeled as cooler in the primary loop should be replaced by the actual plate fin heat exchanger with real parameters and its effect should be observed in the loop.
- In the present study, the heat exchanger used in the secondary loop is shell and tube type in the present study whereas in actual implementation it is supposed to be a plate fin heat exchanger and hence should be simulated with a plate fin heat exchanger with actual sizing values.
- The actual sizing values for pump, compressor and heater/magnet should be used and the alternate design should be discussed so as to place the heat exchangers in the liquid helium bath.

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Appendix A

Simulation Results Snapshot

A.1 Simulation Results of Common Cold Compressor with Individual Bath

Here, different snapshots of bath liquid level percentage, bath pressure of CS, TF ,ST and PF magnet, mass flow IN/OUT of the cryo plant, heat load profile of CS, TF, ST and PF magnet cooling system are shown :

A.1.1 Bath Liquid Percentage Level

The snapshot of simulation is shown in Fig. A.1. The level is in percentage (%) of vessel/bath volume.

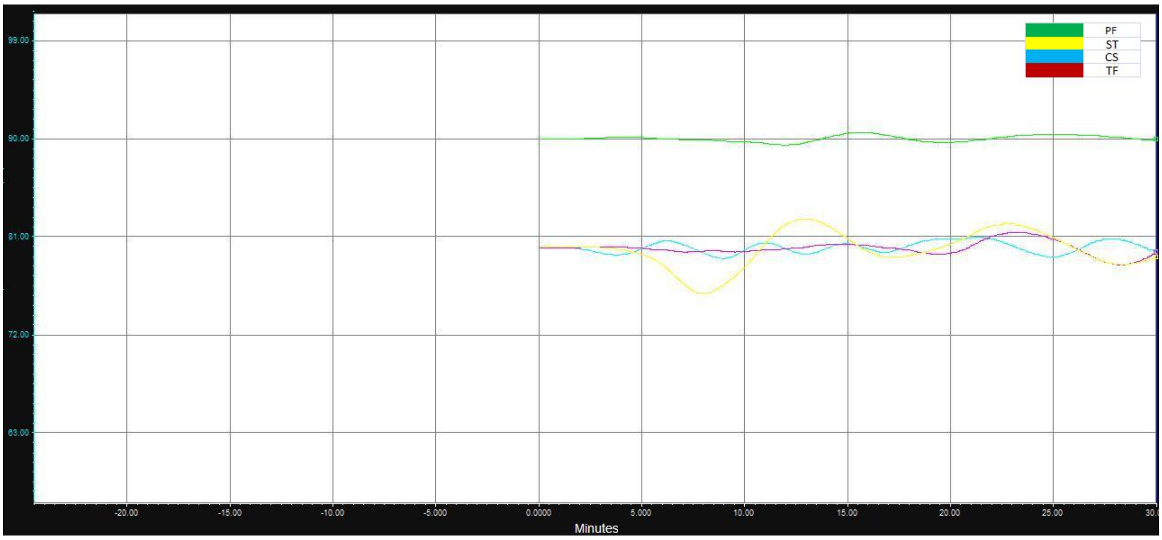

Figure A.1: Bath LPL

A.1.2 Mass Flow IN/OUT of the Cryo Plant

The mass flow IN/OUT of the cryo plant is shown in Fig. A.2. The mass flow is in kg/sec w.r.t time in seconds.

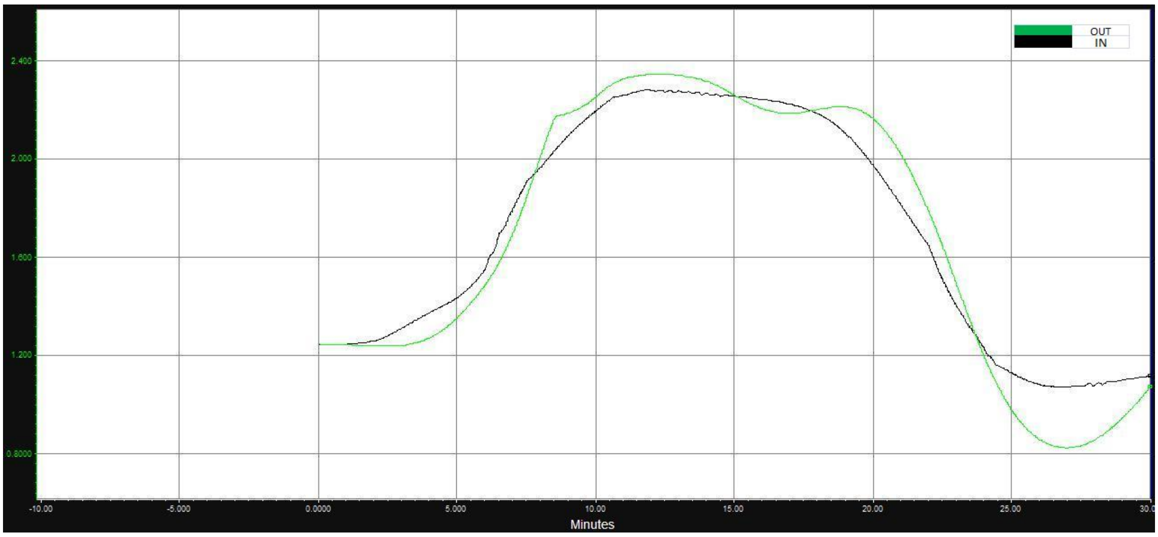

Figure A.2: Mass Flow

A.1.3 Vessel/bath Pressure Variation

The vessel/bath pressure variation is shown in following Figures for CS,TF,ST and PF. The bath Pressure variation is in bar with time in seconds.

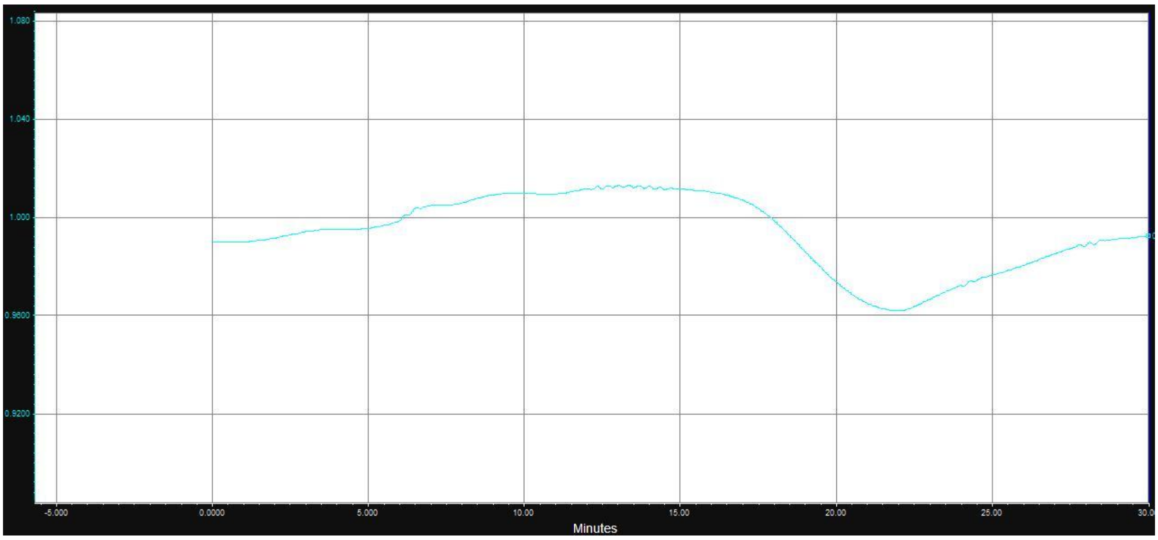

Figure A.3: Vessel pressure of CS

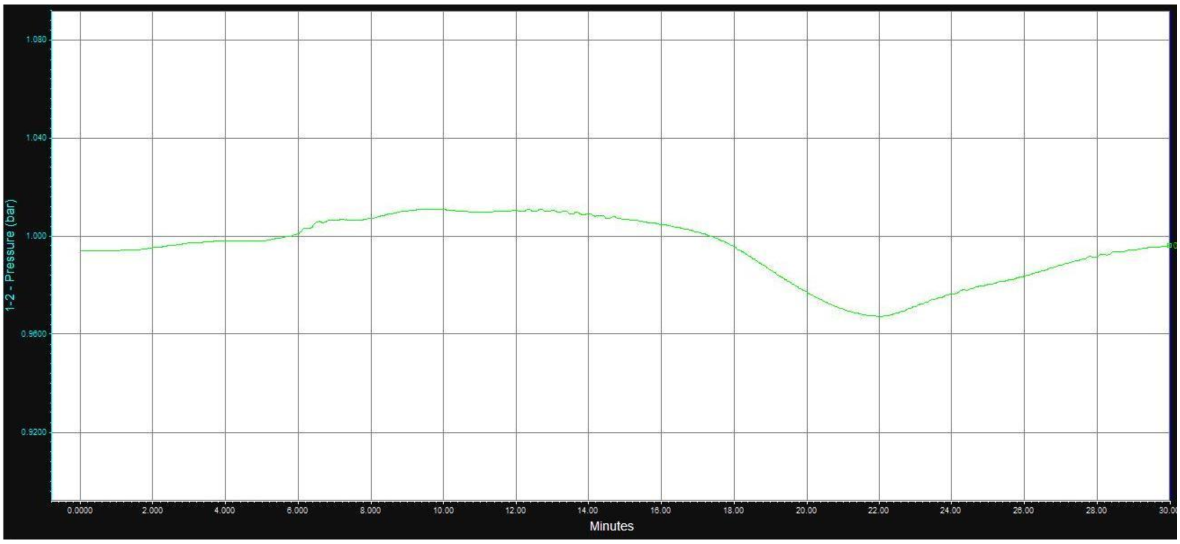

Figure A.4: Vessel pressure of TF

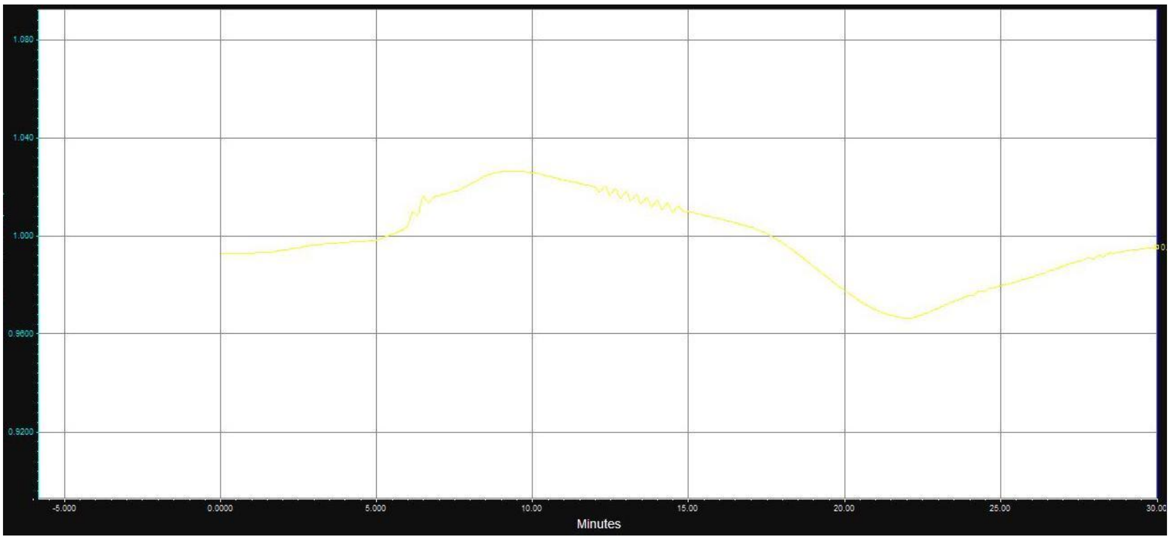

Figure A.5: Vessel pressure of ST

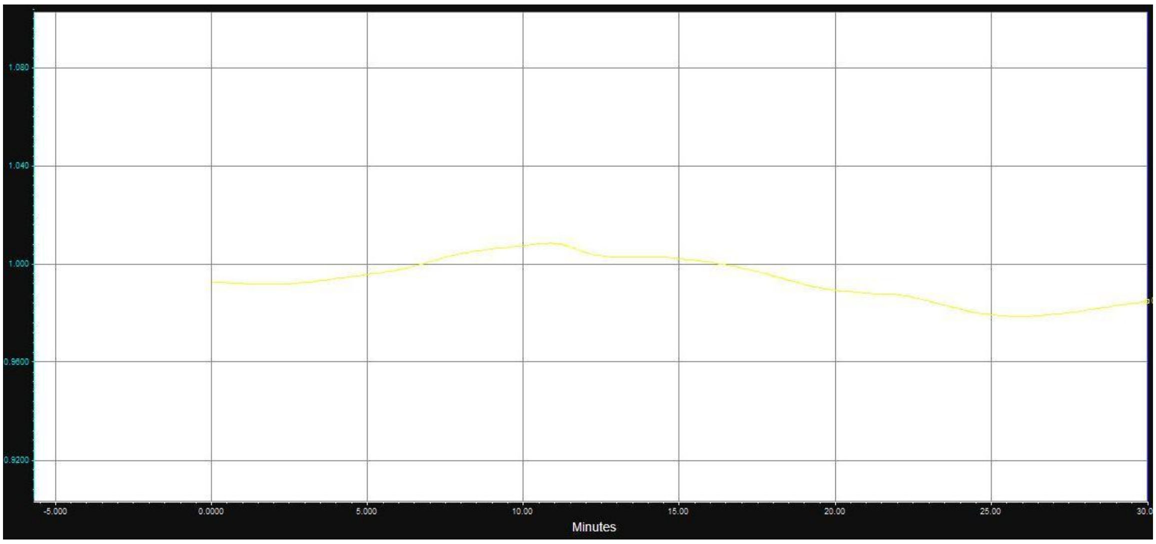

Figure A.6: Vessel pressure of PF

A.1.4 Heat Load Profile of Magnets (CS,TF,ST & PF) and its associated Equipments

The heat load profile of magnets and its associated equipments like pump power, compressor power, heat duty of heat exchanger/cooler 1/2 and combined heat duty of both these heat exchangers/coolers. The unit of all the heat duty and power is in kilowatt (kW) with time (in seconds) on another axis.

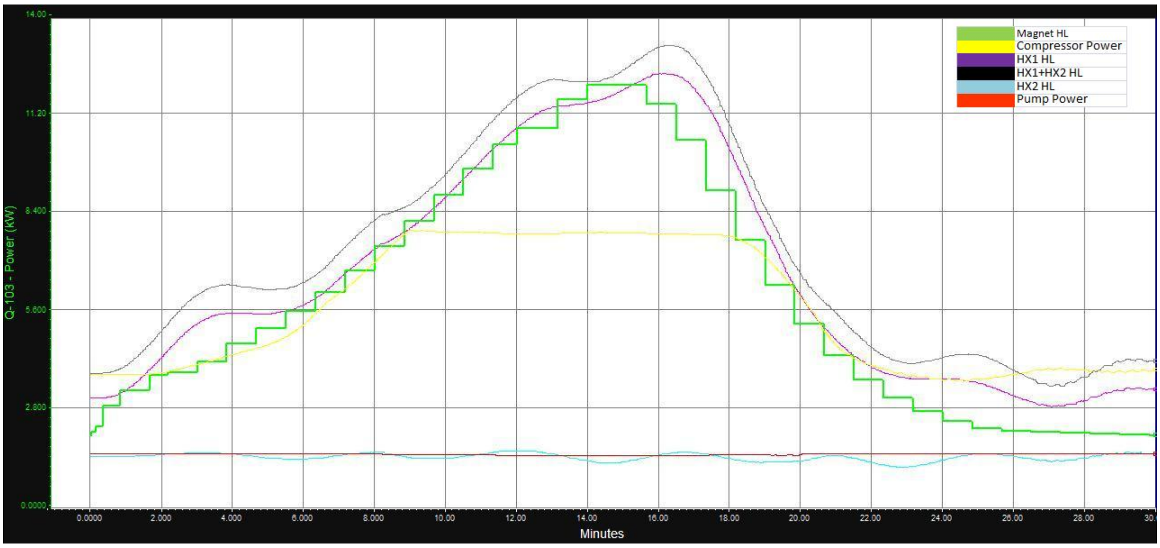

Figure A.7: Heat load profile of CS magnet

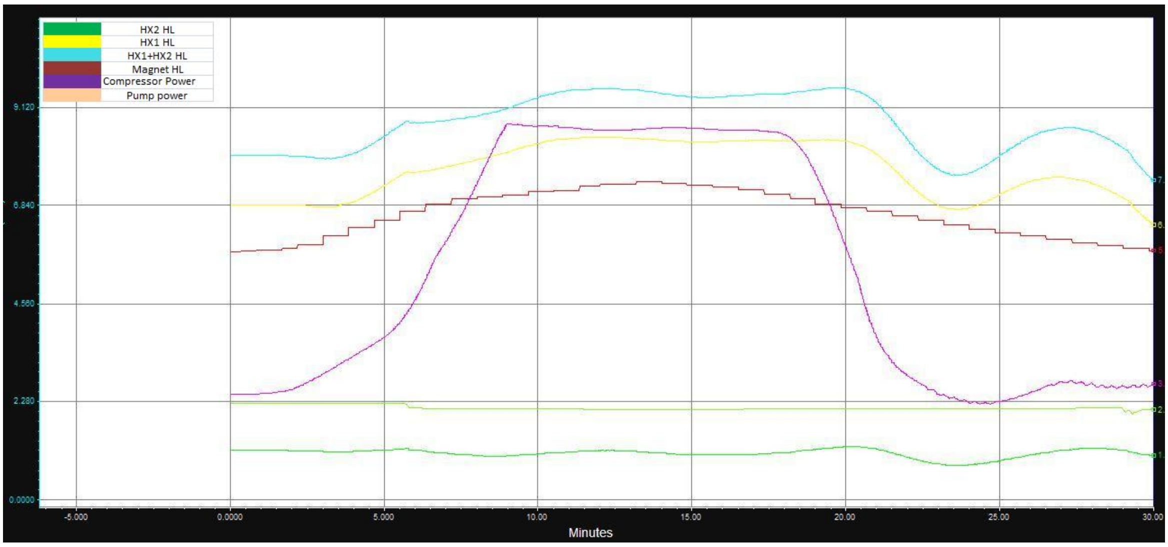

Figure A.8: Heat load profile of TF magnet

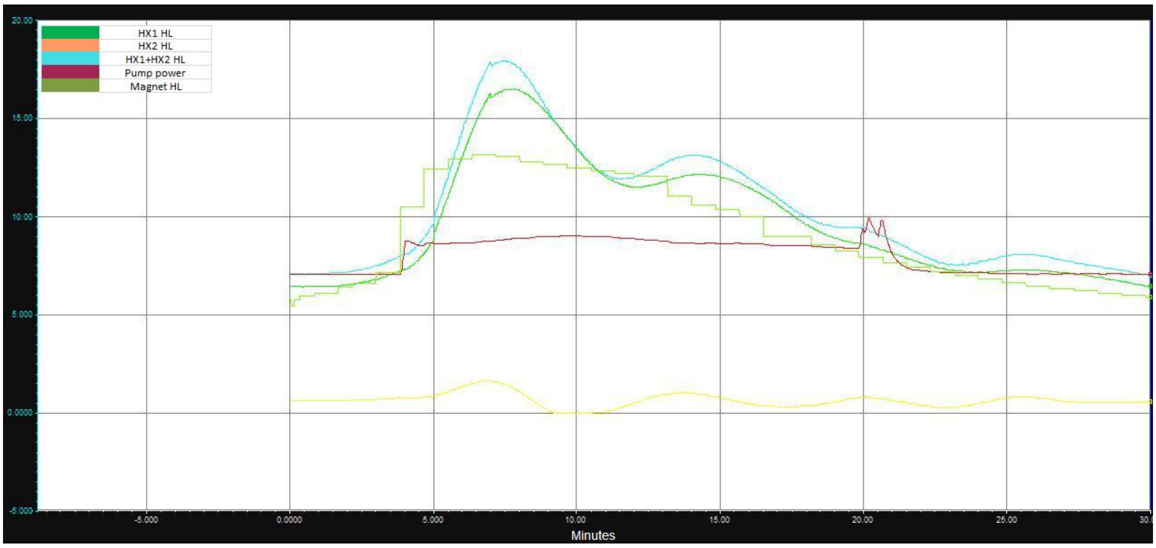

Figure A.9: Heat load profile of ST magnet

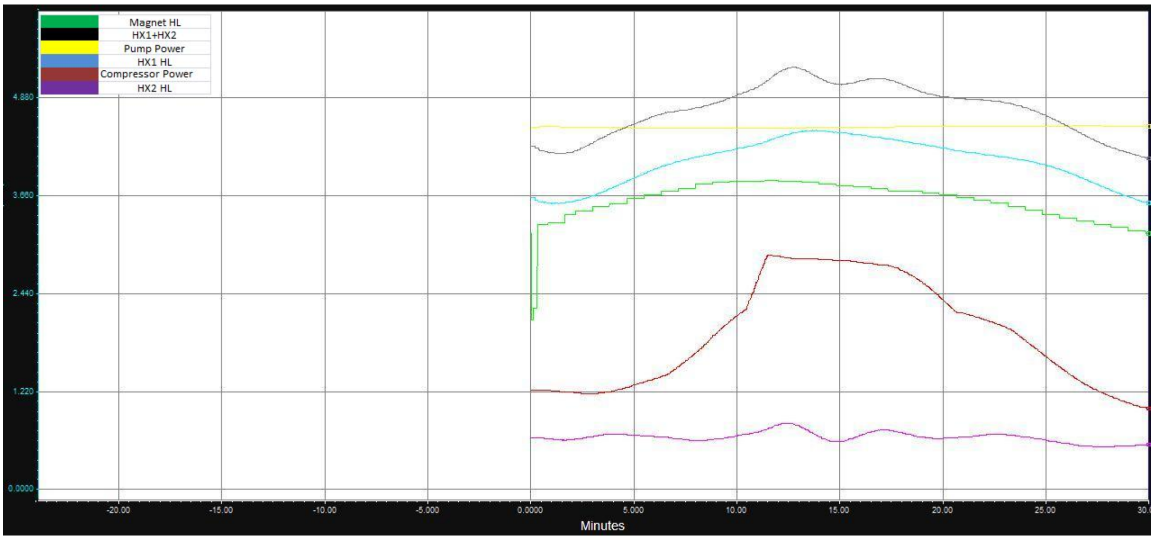

Figure A.10: Heat load profile of PF magnet

A.2 Simulation Results for Common Liquid Helium Bath and Common Cold Compressor

A.2.1 Bath Liquid Percentage Level

The bath liquid percentage level is shown in Fig. A.11 for PF and common bath/vessel.

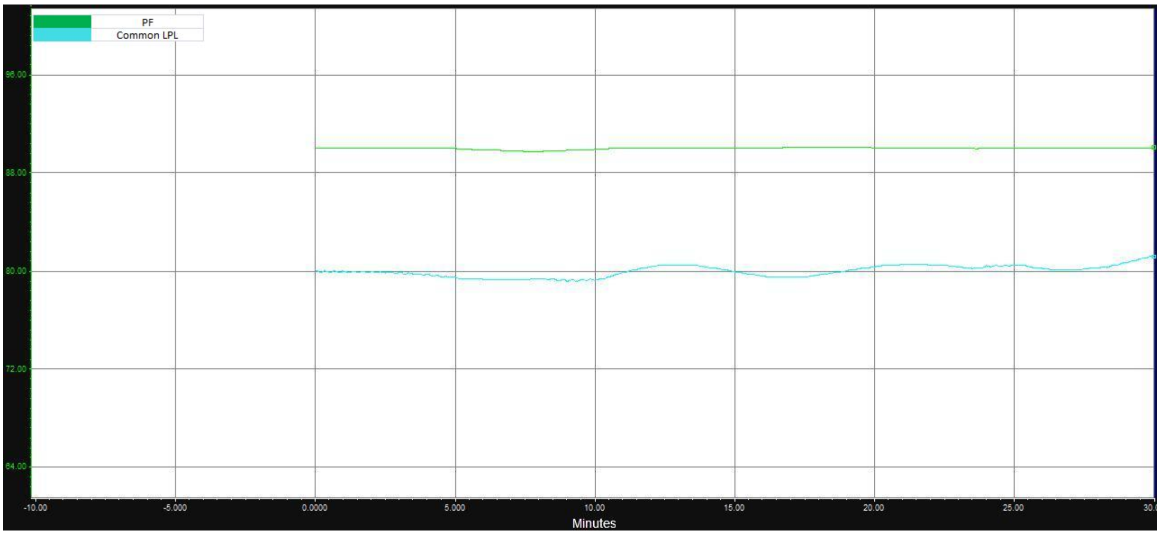

Figure A.11: Bath liquid percentage level

A.2.2 Mass Flow IN/OUT of the Cryo Plant

The mass flow IN/OUT of the cryo plant is shown in Fig. A.12. The mass flow is in kg/sec and time in seconds.

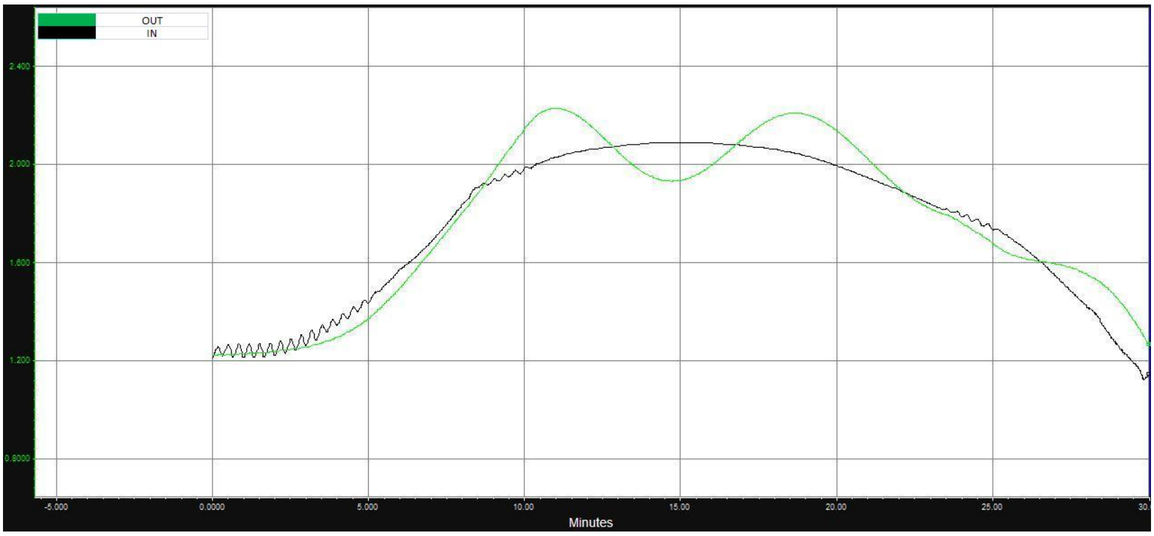

Figure A.12: Mass Flow

A.2.3 Bath pressure variation

The bath pressure variation is shown in Fig. A.13. The pressure is in bar and time in seconds.

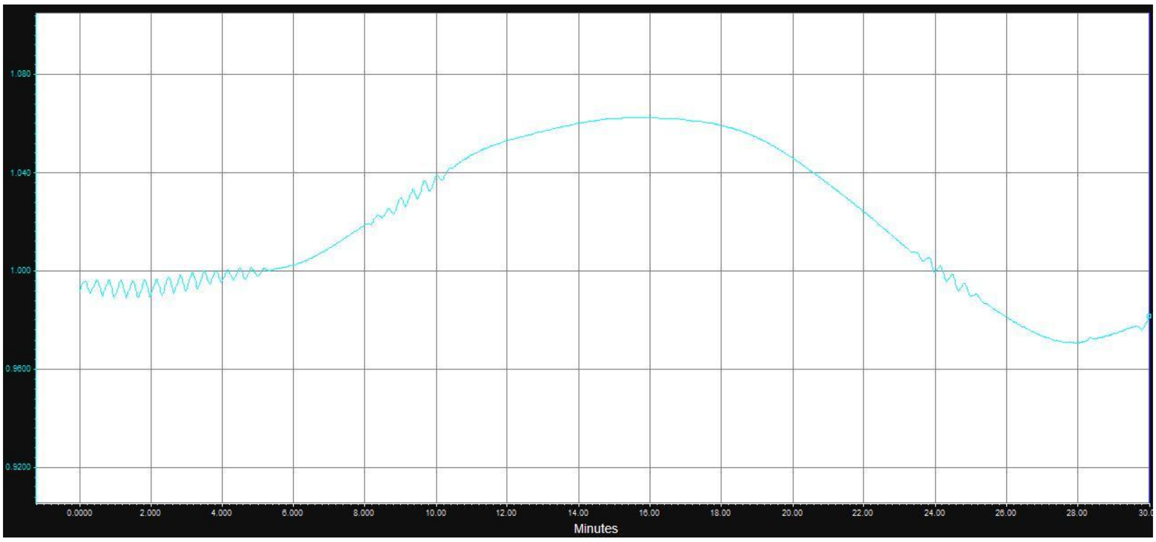

Figure A.13: Bath Pressure Variation of CS

A.2.4 Heat Load Profile of Magnets (CS, TF, ST & PF) and Associated Equipments

The heat load profile of magnets and its associated equipments for individual cooling system of a magnet is shown in following Figures. The main components are compressor and pump power, heat duty of HX1 and HX2 heat exchangers/coolers. The unit of heat duty is kilowatt (kW).

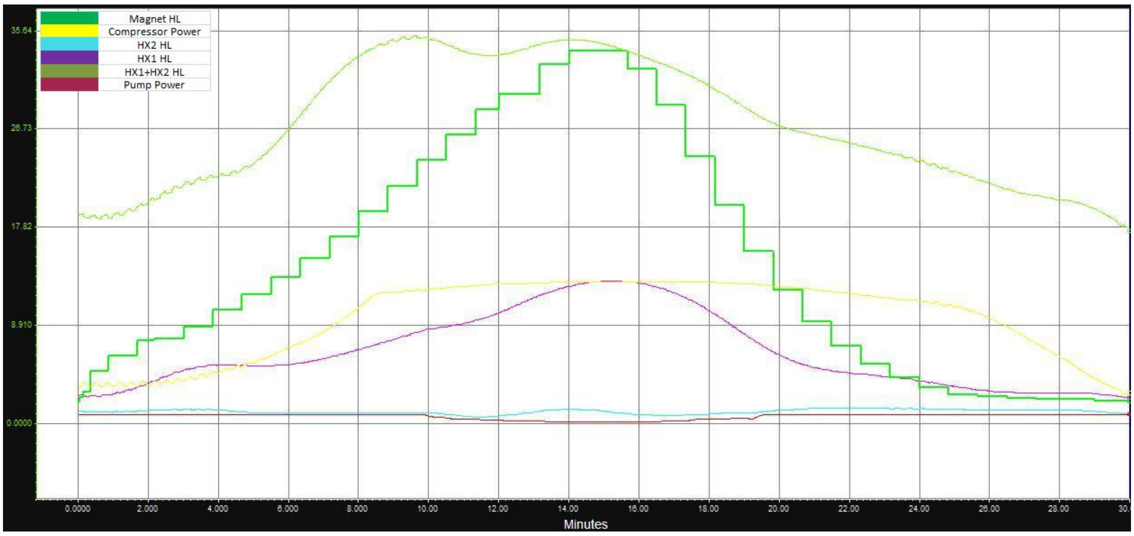

Figure A.14: Heat load profile of CS magnet

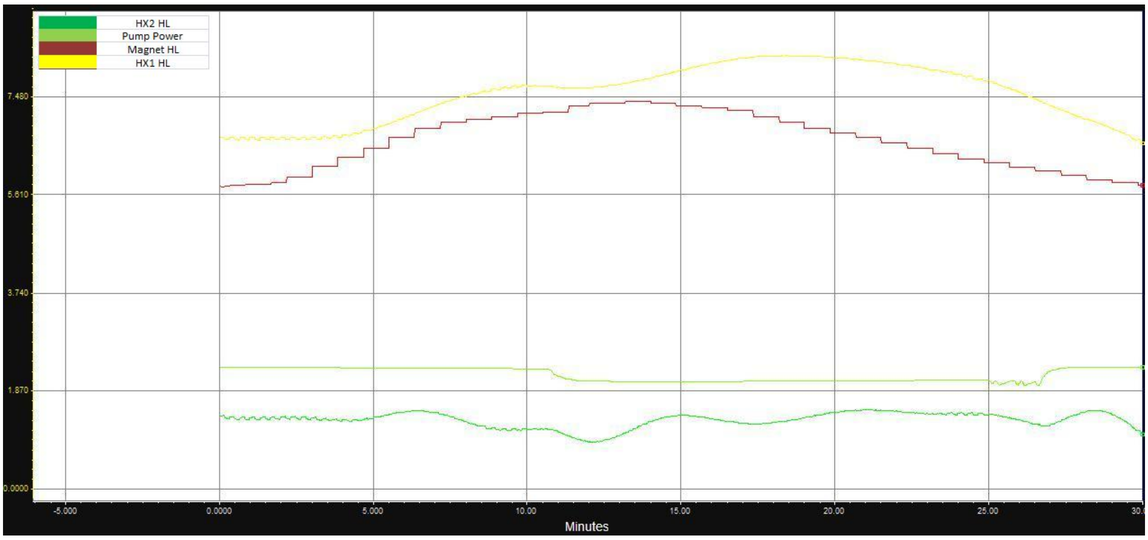

Figure A.15: Heat load profile of TF magnet

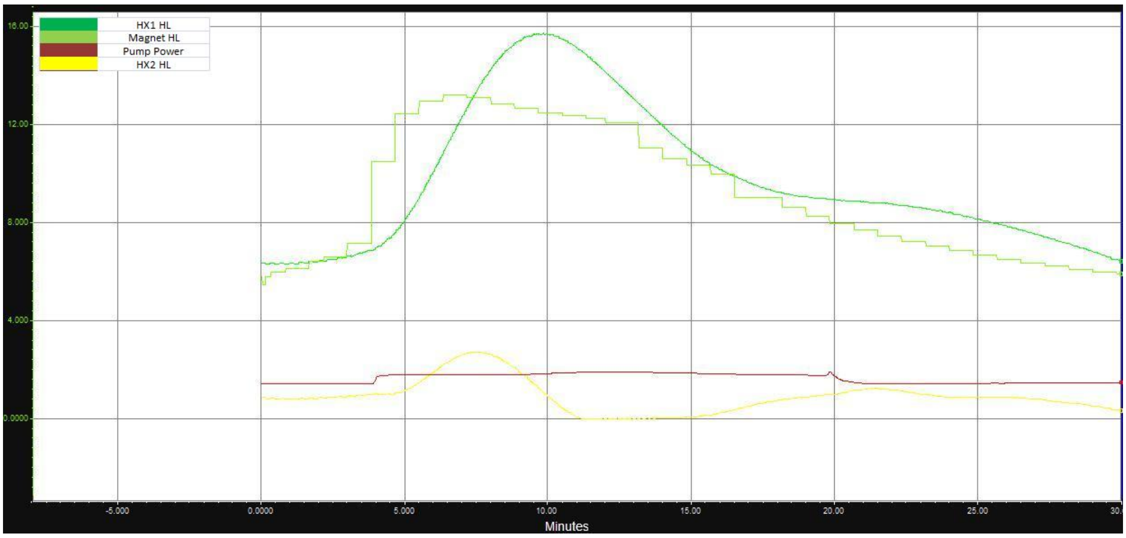

Figure A.16: Heat load profile of ST magnet

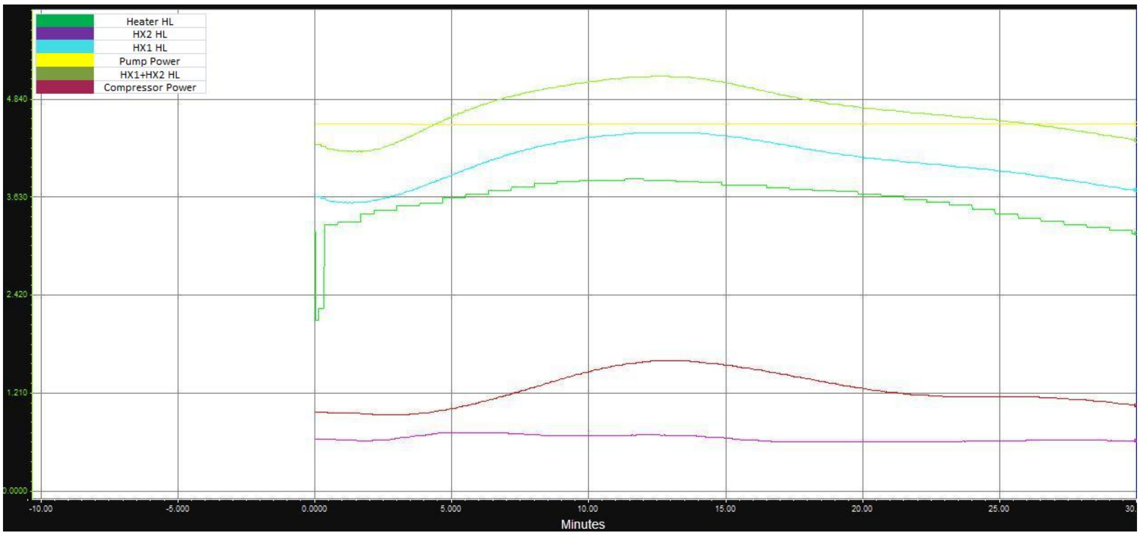

Figure A.17: Heat load profile of PF magnet

A.3 Individual Cold Compressor with Individual Bath

A.3.1 Bath Liquid Percentage Level

The liquid percentage level is shown in Fig. A.18 for CS, TF and ST magnet.

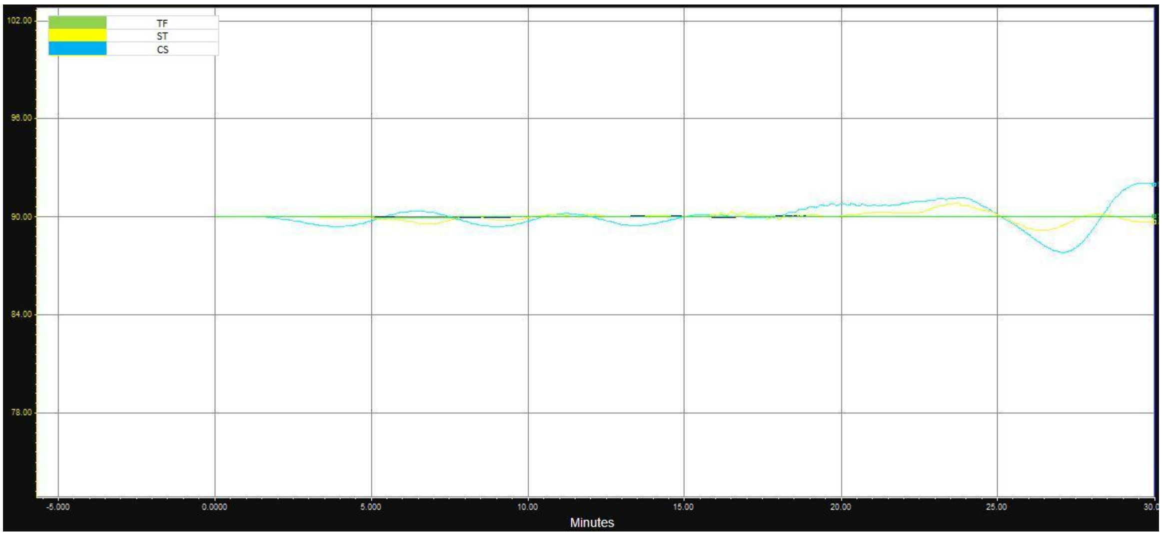

Figure A.18: Bath liquid percentage level

A.3.2 Mass Flow IN/OUT of the Cryo Plant

The mass flow IN/OUT of the cryo plant is shown in Fig. A.19. The mass flow is in kg/sec and time in seconds.

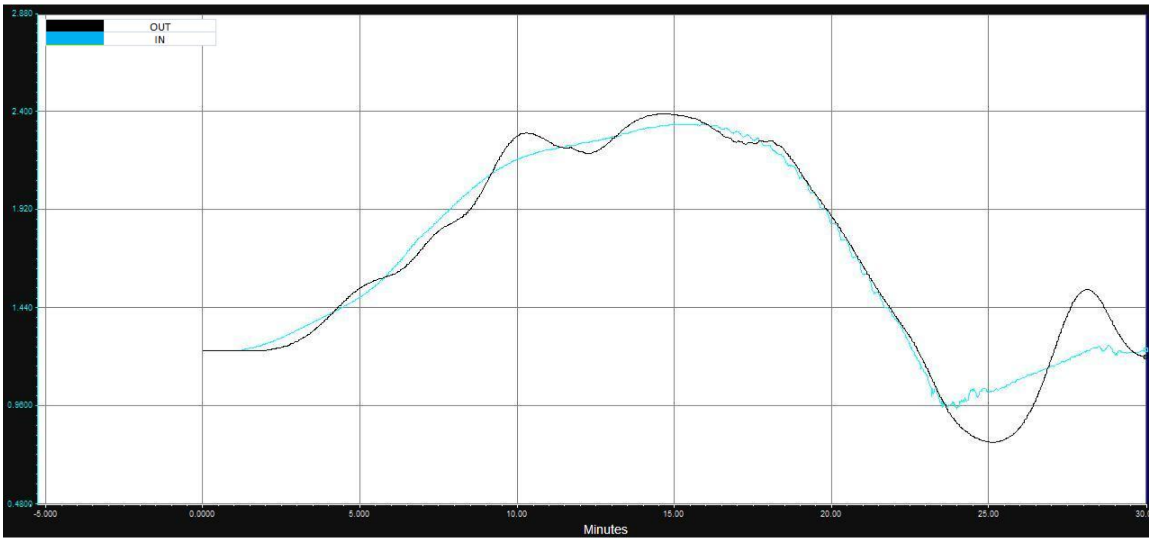

Figure A.19: Mass Flow

A.3.3 Vessel/Bath Pressure Variation

The vessel/bath pressure variation is shown in following Figures for CS, TF, ST and PF magnets respectively. The pressure variation is in bar w.r.t time in seconds.

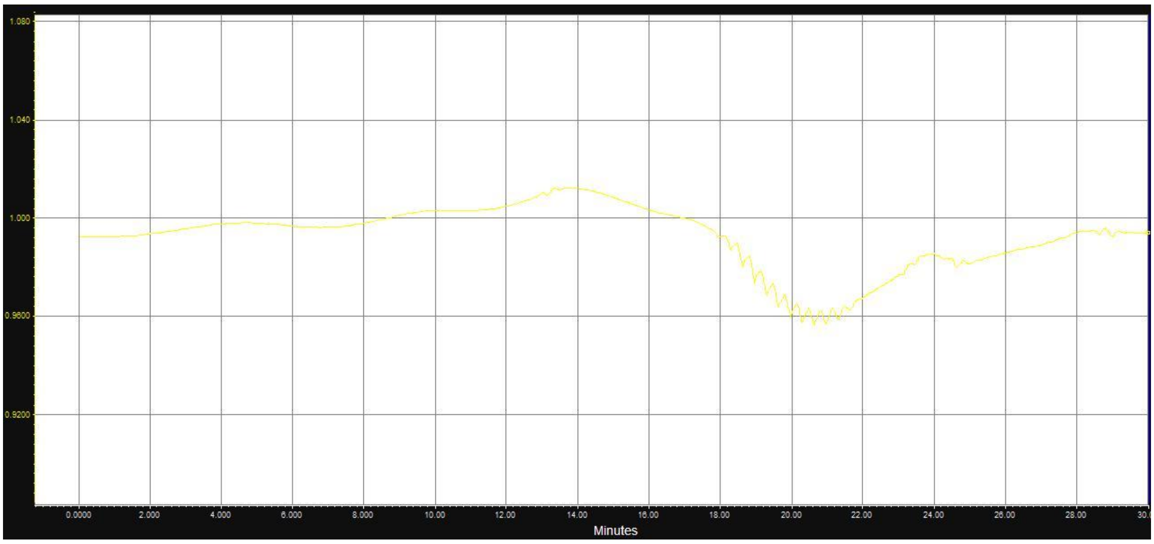

Figure A.20: Bath Pressure Variation of CS

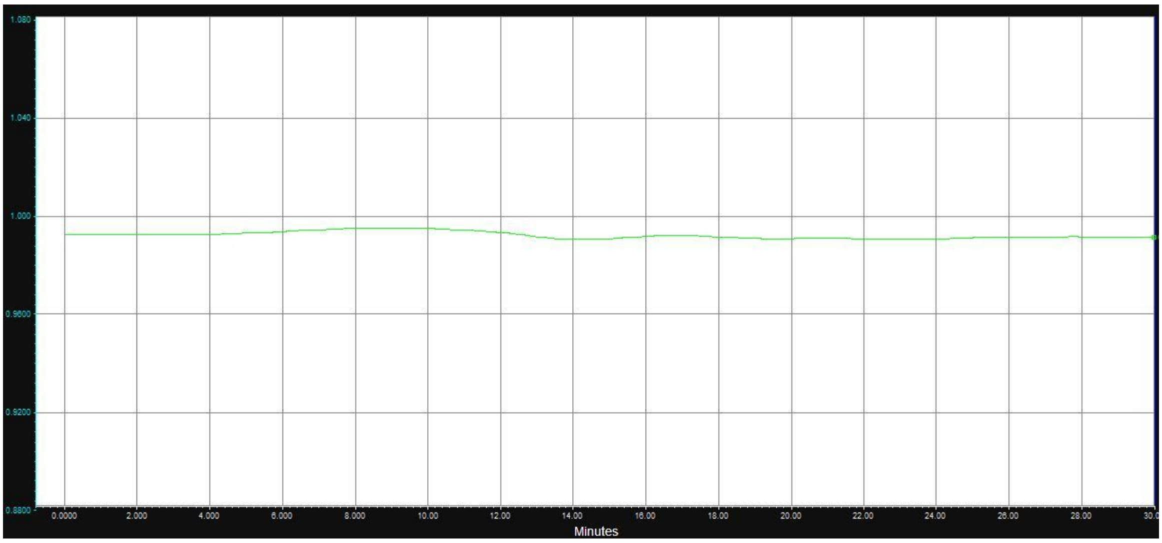

Figure A.21: Bath Pressure Variation of TF

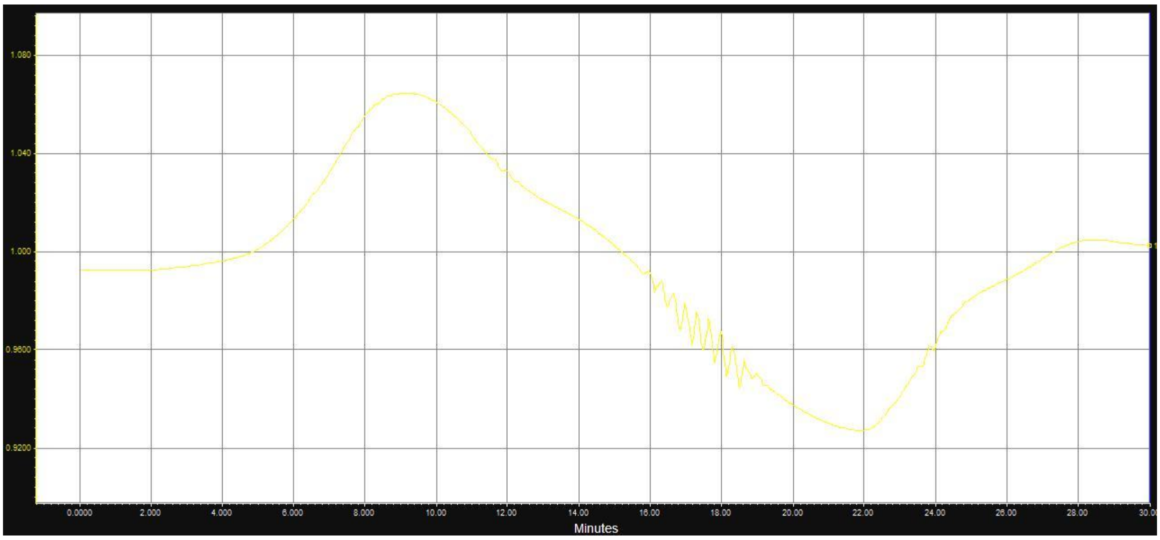

Figure A.22: Bath Pressure Variation of ST

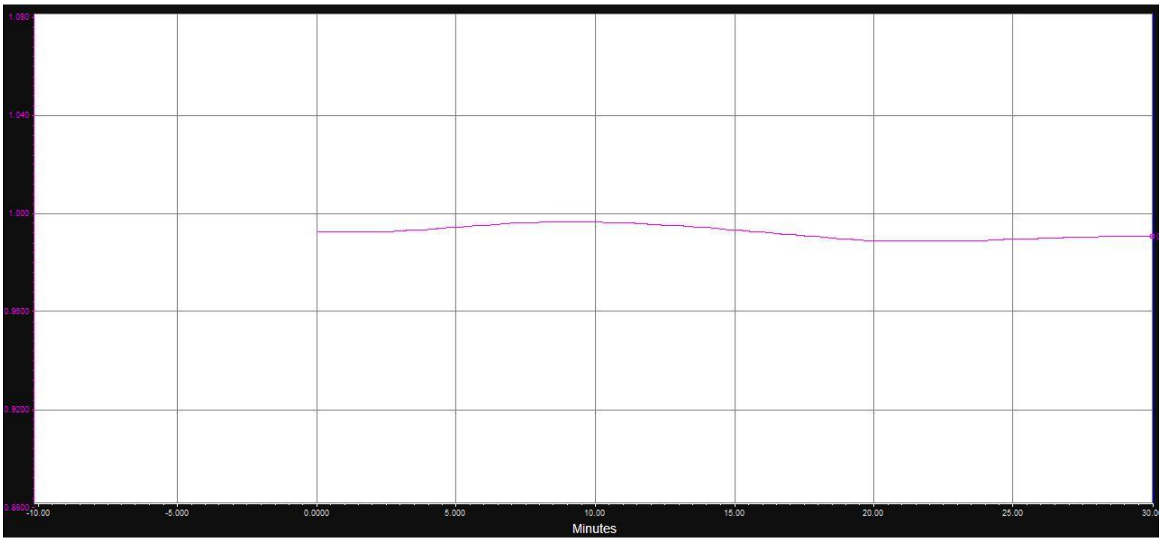

Figure A.23: Bath Pressure Variation of PF

A.3.4 Heat Load Profile of Magnets (CS, TF, ST & PF) and its Associated Equipments

The heat load profile of magnets and its associated equipments for individual cryogenic system is shown in following Figures. The heat duty unit is in kilowatt (kW) w.r.t time in seconds.

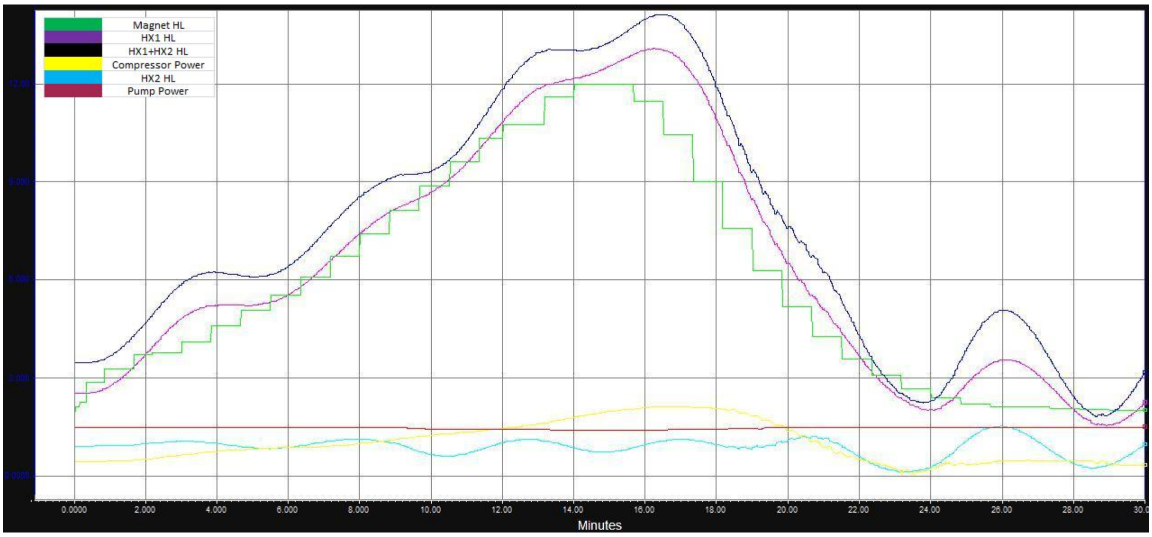

Figure A.24: Heat load profile of CS magnet

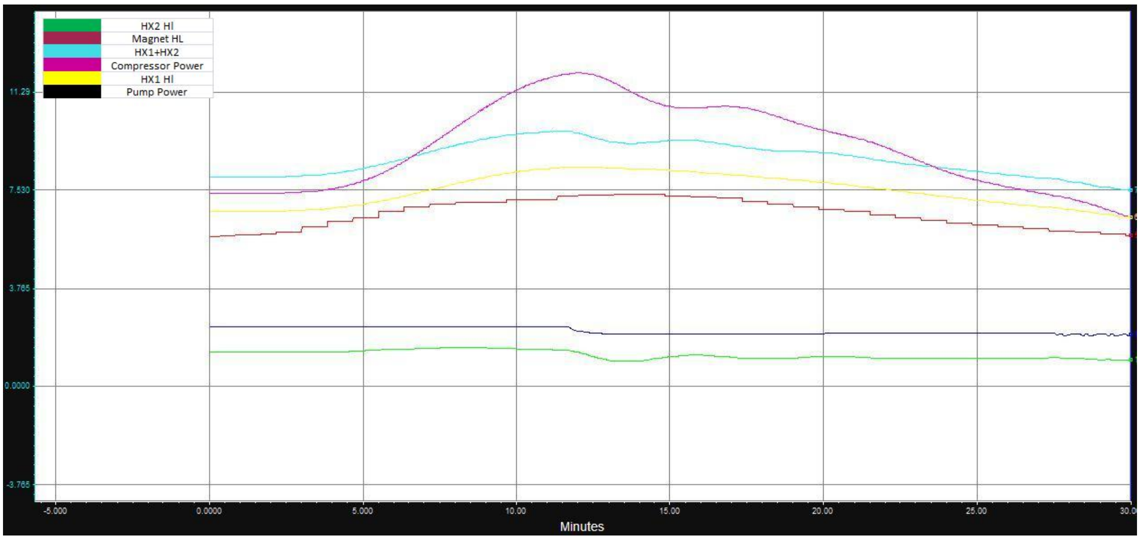

Figure A.25: Heat load profile of TF magnet

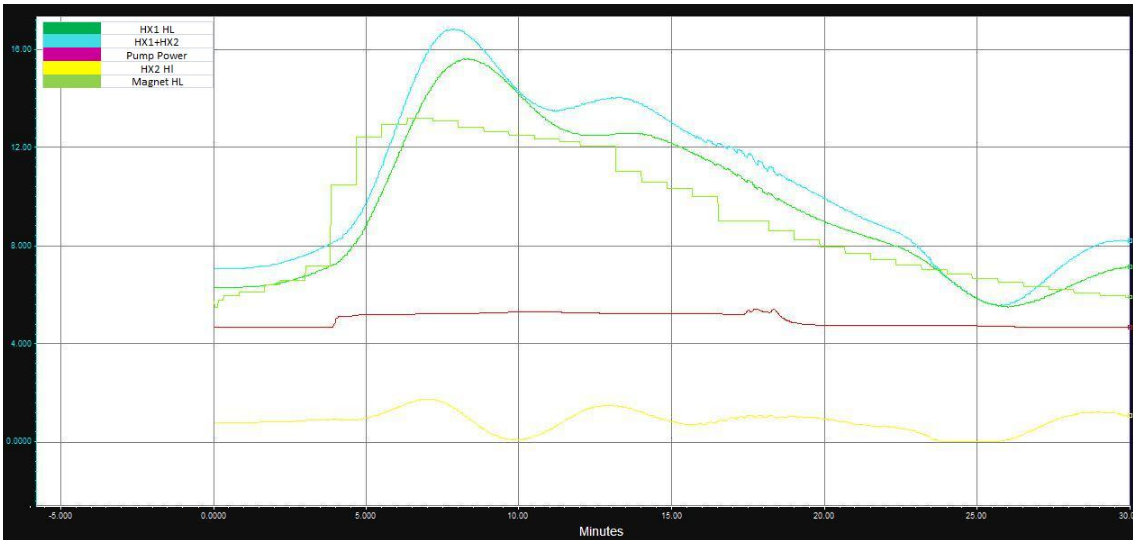

Figure A.26: Heat load profile of ST magnet

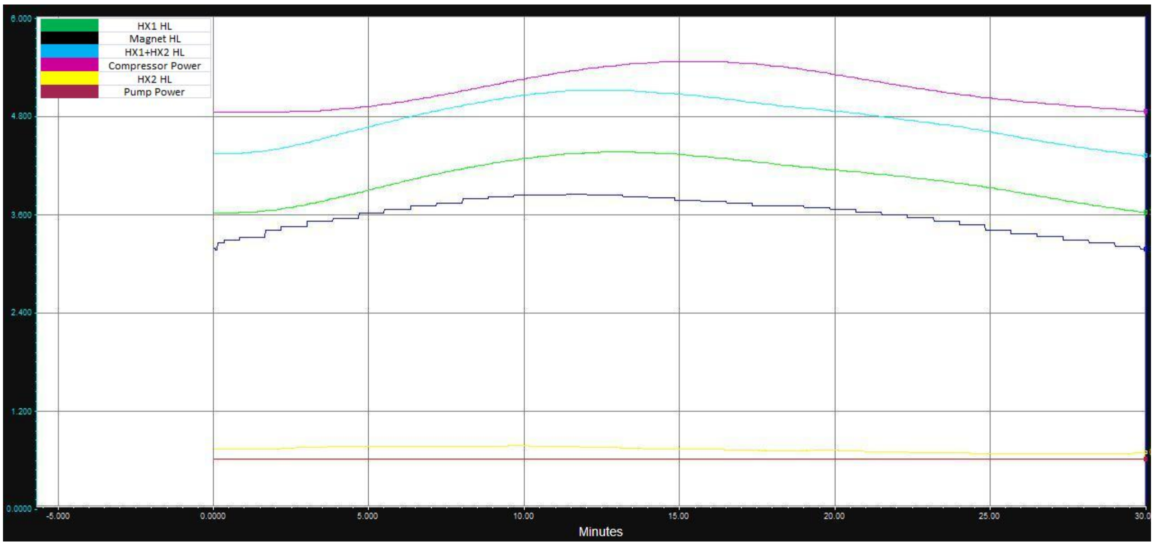

Figure A.27: Heat load profile of PF magnet