

Electric Aircraft with HTS (High Temperature Superconductor) Motor, Design & Simulation



A thesis submitted in partial fulfilment for the degree of B.Sc in
Electrical & Electronic Engineering

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DECLARATION

We hereby declare that the thesis titled “Electric Aircrafts with HTS motors, design and simulation”, a thesis submitted to the Department of Electrical and Electronics Engineering of BRAC University in partial fulfillment of the Bachelor of Engineering in Electrical and Electronics Engineering. This is our original work and was not submitted elsewhere for the award of any other degree or any other publication

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List of Figures

- Fig: 1.51 Perfect diamagnetic property of superconductor (Meissner effect)
- Fig: 1.52 Superconductivity in a 3D space defined by current density, temperature, and magnetic field
- Fig: 2.1 DC-3 by Douglas Aircraft (left); A sample of NACA airfoil (right)
- Fig: 2.2 Great Britain's BOAC was the first to begin commercial jet aircraft operations, in May 1952
- Fig: 2.3 A conventional aircraft
- Fig: 2.4 D8.5, a modified version of D8
- Fig: 2.5 Top-view and side-view of the D8.5
- Fig: 2.6 NASA N+3 Metrics and performance of D8.5
- Fig: 2.7 D8.5 layout
- Fig: 2.8 Blueprint of D8 on Solidworks
- Fig: 2.9 D8 model designed in Solidworks
- Fig: 2.10 Airfoil of D8
- Fig: 2.11 Fluent module of Ansys
- Fig: 2.12 Varying components of force
- Fig: 2.13 Graph of C_L vs. α for Aurora D8.5
- Fig: 2.14 Typical C_L vs. α plot for a positively cambered aerofoil
- Fig: 3.1 Critical temperatures and year of discovery for different superconductors
- Fig: 3.2 Crystalline structure of YBCO
- Fig: 3.3 Performance comparison of YBCO and Bi-2223 superconducting wires at various temperature and magnetic field
- Fig: 3.4 Overview of AMSC HTS wire manufacturing process
- Fig: 3.5 SuperPower HTS wire configuration
- Fig: 3.6 AC synchronous machine with YBCO winding
- Fig: 3.7 Magnetization loop for a full cycle of applied field

Fig: 3.8	1MW Propulsion Motor
Fig: 3.9	Block diagram of the HTS system
Fig: 3.10a	2D Racetrack Model
Fig: 3.10b	3D Racetrack Model
Fig: 3.11	Cross Section Area of racetrack model
Fig: 3.12	Overall dependency of $J_c(B_y, B_x)$
Fig: 3.13	Instantaneous and average loss of a racetrack coil 1MW motor
Fig: 3.14	Instantaneous and average loss of a racetrack coil of 1.25MW motor
Fig: 3.15	Instantaneous and average loss of a racetrack coil of 1.5MW motor
Fig: 4.1	Classification of cryocooler
Fig: 4.2	Different types of cryocooler
Fig: 4.3	Schematic representation of cryocooler
Fig: 4.4	Systematic representation of thermodynamic process involved in ideal Stirling cycle
Fig: 4.5	StirlingCryocooler with schematic representation
Fig: 4.6	Four steps involved in cooling cycle
Fig: 4.7	Braytoncryocooler with counter flow heat exchanger (HX2) for cooling liquid nitrogen (LN)
Fig: 4.8	Schematic temperature distribution of liquid nitrogen (LN) and refrigerant (REF) in HX2, depending on the relative magnitude of capacity rate of two streams
Fig: 4.9	FOM of ideal Brayton cycle as a function of pressure ratio for various values of heat exchanger effectiveness
Fig: 4.10	FOM of practical Brayton cycle as a function of pressure ratio for various values of highest pressure with helium and neon as refrigerant
Fig: 4.11	FOM as a function of pressure ratio to compare single-stage and two-stage compressions
Fig: 4.12	FOM as a function of pressure ratio for various values of high pressure with helium, two-stage compression, and wall-temperature constraint to avoid freezing of liquid nitrogen
Fig: 4.13	Designed Brayton-cycle cryocooler on temperature-entropy diagram of helium
Fig: 4.14	Temperature range for different regenerator materials used in cryocooler
Fig: 4.15	Schematic diagram of Reverse BraytonCryocooler
Fig: 4.16	Relationship between specific mass & $\log_{10}$ of input power for known RBCC

Fig: 4.17	Mass of cryocooler vs Input power
Fig: 4.18	Single stage Brayton cycle efficiency
Fig: 4.19	Difference of temperature ration with and without regenerator
Fig: 4.20	Simulation data of efficiency vs pressure
Fig: 4.21	Schematic overview for the single-stage model
Fig: 4.22	Superconducting temperature vs Mass for 2 nd stage RBCC
Fig: 4.23	Ansys graph at different temperature and mass
Fig: 4.24	Solid Model in Ansys
Fig: 4.25	Meshing of solid model in Ansys
Fig: 4.26	Temperature profile of model at B=0T
Fig: 4.27	Temperature and pressure data of Ansys
Fig: 5.1	Minimum True Velocity vs Lift coefficient
Fig: 5.2	Lift co-efficient Vs Angle of attack
Fig: 5.3	Minimum required velocity vs Air density
Fig: 5.4	Electric Filed vs Current Density
Fig: 5.5	Surface current density
Fig: 5.6	Current density vs Magnetic Flux density
Fig: 5.7	Variation of surface magnetic flux density
Fig: 5.8	Resistivity Vs normalize current
Fig: 5.9	Pin vsTh
Fig: 5.10	Mass vs Input power

List of Tables

Table: 2.1	Aircraft parameters
Table: 2.2	Horizontal & vertical components for different α
Table: 2.3	Lift Co-efficient, C_L for different α (angles of attack)
Table: 3.1	1MW Propulsion motor design parameters
Table: 3.2	Racetrack coil parameters
Table: 3.3	Variables for calculating the parameters for loss
Table: 3.4	Tabulated simulated results for different motor
Table: 4.1	Thermodynamic properties of helium for designed cycle
Table: 4.2	Material properties of Er_3Ni for ANSYS
Table: 4.3	List of RBCC cryocooler found with known mass, input power & their respective practical application
Table: 4.4a	Evaluation of the effect of masses & inefficiency on fuel burn
Table: 4.4b	Cryocooler power demand & masses
Table: 4.5	Power demand at different temperature with efficiency
Table: 4.6	Boundary conditions
Table: 4.7	Temperature difference at different magnetic Flux of the hts motor
Table: 5.1	Result of ground velocity for different lift coefficient
Table: 5.2	Simulated and theoretical value of lift coefficient with different angle of attack
Table: 5.3	Minimum velocity at different densities
Table: 5.4	Parameters for equation 5.3
Table: 5.5	Parameters for equation 5.4
Table: 5.6	Different input power for different masses of the cryocooler

Table of Contents

List of Figures	03
List of Tables	06
Acknowledgement	10
Abstract	11
Chapter 1: Introduction	12
1.1 Literature Review	12
1.2 Motivation of the Work	14
1.3 Research Objective	14
1.4 Electric Aircraft in General	15
1.5 Brief Description of HTS Material	15
1.6 Cryocooler	17
1.7 Contribution of the Research	18
1.8 Thesis Organization	19
Chapter 2: Aircraft Configuration Analysis	20
2.1 Aircraft Configuration Background	20
2.2 The Double Bubble ‘D8’ Concept	22
2.2.1 Design Features & Benefits	24
2.3 Configuration Geometry & Dimension	26
2.4 Simulation & Results In CFD Solver, ANSYS Fluent	29
2.5 Summary	32
Chapter 3: HTS Motor & Simulation Of HTS Racetrack Armature	
Coil Made Up Of YBCO Using COMSOL 5.3	33
3.1 Introduction	33
3.2 HTS material (YBCO)	33
3.2.1 Commercial HTS wire	36
3.3 Application of HTS in electric machine & motor working principal	37

3.4 AC Loss In HTS Conductors	39
3.4.1 Magnetization Loss	40
3.4.2 Transport Current Loss	42
3.5 HTS Racetrack Coil 3D modelling in COMSOL 5.3 & AC Loss Calculation	43
3.6 Result Analysis	49
3.7 Summary	52
Chapter 4: Cooling System of HTS Motor Using Cryocooler	53
4.1 Introduction	53
4.2 Types of Cryocooler	53
4.2.1 Recuperative Cryocooler	54
4.2.2 Regenerative Cryocooler	55
4.2.2.1 The Joule-Thomson Cryocooler	56
4.2.2.2 Brayton Cryocooler	57
4.2.2.3 Pulse Tube Cryocooler	58
4.2.2.4 Stirling Cryocooler	58
4.3 Transformation Process of Stirling Cryocooler	60
4.3.1 Thermodynamic Process	60
4.3.2 Working Process	61
4.3.3 Cooling Cycle	62
4.4 Analysis and working process of Brayton Cryocooler	64
4.4.1 Thermodynamics Relation of Brayton Cryocooler	64
4.4.2 Achieving The Maximum Value of FOM (ideal cycle)	67
4.4.3 Practical Cycle Design	68
4.5 Heat Exchange and Material properties of Cryocooler	74
4.6 Cryocooler For HTS Aircraft	76
4.6.1 Selection of Reverse Brayton Cryocooler	77

4.7 Results Analysis	78
4.7.1 Relation of Mass, Power Input Temperature Losses & Efficiency	78
4.7.2 Brayton Cycle Efficiency	82
4.7.3 Future Framework of 2 stage RBCC	86
4.7.4 Superconductor & Heat Sink Temperature Boundary Condition	88
4.7.5 Design in ANSYS	90
4.8 Summary	94
Chapter 5: Ansys Simulation, Analysis & Comparison With MATLAB	
Results	95
5.1 Aurora D8 Simulation & Comparison With MATLAB	
Results	94
5.2 HTS Racetrack Coil Property Simulation	103
5.3 Cryocooler Simulation & Comparison With MATLAB	
Results	109
Chapter 6: Conclusion & Future Work	112
6.1 Conclusion	112
6.2 Future Work	113
Reference	114

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Abstract

Evolution of electric aircrafts would allow more efficient, quiet and green transports that would reduce the emission of greenhouse gases along with reduction in the overall flight expenses, which conventional IC engines are incapable of. This thesis concerns the possibility of designing an efficient electrical aircraft by considering AURORA D8 body structure. The AURORA D8 or the double bubble design is currently under development by NASA and is predicted to hit the market by 2035. The aircraft will be powered by HTS motor, the armature coil of which will be made of YBCO. The simulation of the motor is carried out by FEA software COMSOL 5.3. A cryocooler is designed and its simulation is done in ANSYS.

Chapter 1

Introduction

Evolution of electric aircrafts would allow more efficient, quieter, greener transports and would reduce the emissions of greenhouse gases along with reduction in the overall flight expenses, which conventional IC engines are incapable of. The first obstacle for an efficient electric aircraft is to model a suitable aerodynamic body and for this we have chosen Aurora D8.

Traditional electric motors, cannot supply power density high enough for aerial vehicles. Nowadays HTS material are getting more preference when it comes to electrical power application like motor and generators due to their reasonable advantage in addition compact size, noiseless operation, self-starting torque, light weight and better environmental impact compared to the conventional motors[4]. YBCO a HTS material is used in the armature of our motor..HTS material can have high critical current densities so a very strong magnetic fields can be obtained with much less winding. The AC loss in the coil is simulated using COMSOL with H formulation [6, 7, 18].The coils which are used in the armature are cooled with cryogenics like liquid nitrogen or stationary refrigerator, employing thermo-siphon or gaseous helium loops. The cooling is accomplished with an interface gas like He or N, which transports thermal loads from coils to the stationary refrigerator like a cryocooler. All currently known superconductors must operate at cryogenic temperatures between 4 and 80K.

1.1 Literature Review

The main aspect of an efficient aircraft is its airframe. Throughout recent years many research had been done in order to find the most suitable aircraft configuration for electric aircraft. For example MIT, Aerodyne Research, Aurora Flight Sciences, and Pratt & Whitney have

collaborated to address NASA's desire to pursue revolutionary conceptual designs for a subsonic commercial transport that could enter service in the 2035 timeframe. The final report for the NASA N+3 Phase 1 project "Aircraft and Technology Concepts for an N+3 Subsonic Transport" represents the results of research carried out from 1 September 2008 to 31 March 2010 by a team from MIT, Aerodyne Research, Aurora Flight Sciences, and Pratt & Whitney. This research included development of the conceptual design of two advanced civil aircraft for the 2030-2035 time period, as well as trade studies relating aircraft performance (fuel burn, field length requirement), noise, and emissions for the defined mission to each of the identified advanced technologies, and specific steps needed to advance these technologies. The principal findings are summarized in this section.

The discovery of HTS material has opened many scope in electrical power system such as HTS based motor and generator. Many research are underway to make these innovation more suitable for commercial use. In our thesis we have taken this concept to power an aircraft solely through an HTS motor i.e in other words there would be no usage of fossil fuel. Though it's a new concept and very small research is done on the use of HTS motor in avionics. In the book "Kalsi, S. (2011). Applications of high temperature superconductors to electric power equipment. Hoboken: Wiley" [9] a complete description is given about HTS material like YBCO and its manufacturing process. Furthermore explanation regarding how HTS material is used in rotating machinery and its function are also present. The book also contain the application of HTS material in rotating DC homopolar machine, ac synchronous homopolar machine, and transformer and in power cable. But these are outside the scope of this thesis. In our research we will use the several equation (which will be discussed in chapter 3) from [14] to calculate the parameters of an HTS motor and do the simulation.

Many research has been done on the cooling system (cryocooler) of HTS machine. There are various type of cryocooler which will be further discussed in chapter 4. Some example of research are like the few endeavors to build up a couple of kW levels of Brayton coolers at fluid nitrogen temperature for different applications which is given in literature [30]. In 2007, Hirai et al. [30] built up a model of Brayton cooler (2 kW at 70 K) with a little turbo-expander for HTS power machines. They use neon gas as refrigerant due to their preference in using small turbo-expanders. Recently, Yoshida et al. [38] introduced another plan for 2.5 kW at 65 K with enhanced thermodynamic performance. Sooner than these works, Saji et al. [32] outlined an oil

free turbo-sort of refrigeration with a blend of helium-neon. It was stated that for a reduced refrigeration framework could be designed with 6 kW at 65 K for long 500 MVA cables. In 2008, Breedlove et al. [33] built up a turbo-Braytoncryocooler (1 kW at 95 K) for air-partition in huge airplane.

1.2 Motivation of Work

Electric aircrafts are the future of air transportation and the ultimate solution to the challenges like keeping flight economic, increasing the fuel efficiency, quieter machines and pollutant free air. Moreover, the commercial aircraft industry aims on meeting the emission targets, 75% reduction in CO₂ emission per passenger km, (compared to that in 2000), 55 dB noise reduction, and a 70 % fuel burn reduction by 2050. However, unconventional, more effective technology and alternative aircraft configurations are needed to achieve the goals. Aircrafts with electric propulsion, Boundary Layer Ingestion (BLI), use of high temperature superconductors (HTS) and several other design modifications are to be introduced. The concept of an aircraft combining all these modifications is considered here.

1.3 Research Objective

1. Studying and analyzing the configuration of the aircraft body and checking its aerodynamic efficiency.
2. Designing, transport current loss simulation and efficiency calculation of HTS racetrack coil in motor
3. Checking the varying of efficiency of the cryocooling system with the change of cryocooling liquid.
4. Theoretical and mathematical aspects of increasing efficiency.
5. Analysis of overall efficiency of Aurora D8.5.

1.4 Electric Aircraft in General

In accordance to the growing demand to tackle global warming it is expected that future planes will simply have an electric system. Electric motor are used to power an electric aircraft. This can be achieved in several of ways like using high efficient batteries, ground power cables, solar cells, ultra-capacitors, fuel cells and power beaming. Some of the normal advantages are

Improved aircraft maintainability: No hydraulic components, faster aircraft turnarounr and fewer necessary tools and spares

Improved system availability and reliability: More easily reconfigurable i.e electrical distribution is more practical and offers system reconfiguration flexibility

1.5 Brief Description of HTS material

In metals, for example, copper and aluminum, electricity is conducted as outer energy level electrons share its electrons with other atoms. These atoms forms a vibrating grid inside the metal conductor because of some fixed charged particles; with increasing temperature the vibration of these particle increases. As the electrons start traveling through the metal structure, it collides with tiny impurities or any deformation in the lattice. The electron loses energy in the form of heat. But in case of superconductor material the conduction process is totally unique. The impurities and lattice are still present, however the flow of the superconducting electrons through the material structure is different. As the superconducting electrons travel through the conductor, they go unhindered through the complex lattice structure. Because there is no collision the conduction of electricity can occur without any loss of heat. However, in general superconductor the material temperature has to drop to a certain amount in order to conduct electricity with no resistance. In other words superconductivity is a wonder when the electrical resistivity of the material turns out to be precisely zero when it is cooled underneath a critical

temperature T_c . The operating temperature of superconductor is usually around 4 to 0K which is very hard to maintain, but HTS (high temperature superconductor) are material whose T_c are around 70 to 100K [9]. Another exceptional property of a superconductor is that it totally rejects outer attractive field. This is known as the Meissner effect which was discovered in 1933 Walther Meissner and Robert Ochsenfeld. As indicated by this, a superconductor show perfect diamagnetic property i.e. there is no attractive field inside the superconducting material. The property stays valid when the applied field is small/weak, which is below the critical magnetic field (H_c) and it is cooled underneath its basic temperature (T_c) [8]. It occurs because of formation of electric streams close to its surface. The magnetic field set up by these surface currents cancels the applied magnetic field within the bulk of the superconductor. All these factor makes HTS material ideal for power application like motor and generators.

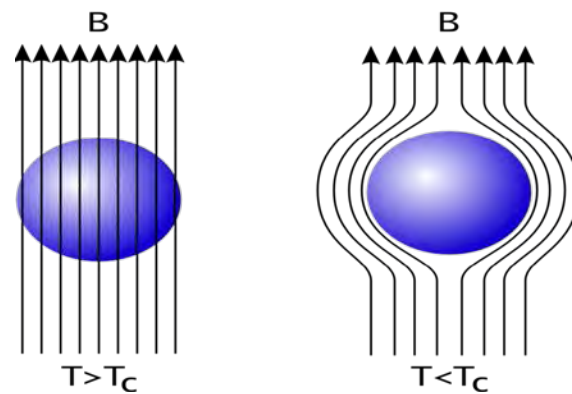


Fig: 1.1 Perfect diamagnetic property of superconductor (Meissner effect)

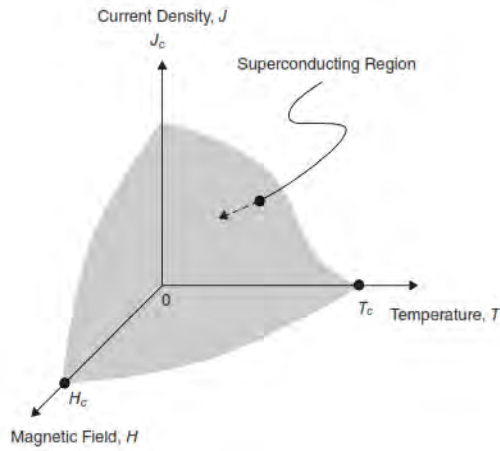


Fig: 1.2 Superconductivity in a 3D space defined by current density, temperature, and magnetic field [9]

All superconductors must function within a regime bounded by three inter - related critical meters current density, operating temperature, and magnetic field as appeared in fig 1.52. The maximum temperature at which a material has no electrical resistivity (displays superconductivity) is called its critical temperature T_c and its highest current carrying capacity is known as the critical current density J_c . The critical magnetic field H_c is the value above which the material stops to be a superconductor. The superconductor will return to its ordinary state if any of these limits is surpassed. The most common HTS conductors are BSCCO - 2212, BSCCO - 2223, YBCO - 123 and MgB_2 . In these paper YBCO-123 is used as an armature winding in designing of the motor.

1.6 Cryocooler

A standout amongst those the greater part significant element from claiming HTS propulsion frameworks clinched alongside airplane may be system for cooling. Aviation cryocooler are by and large for exceptionally low power (W instead of kW). Constantly on right now known superconductors must work at cryogenic temperatures around 80 K [16]. The engineering about making low temperatures is very much complex, Furthermore an incredible bargain of creativity is required with fabricate cooling gear (called refrigerators alternately basically cryocooler) fit of accomplishing these low temperatures [17]. Since superconductors require operation at cryogenic temperature, those cooling framework is an essential to the airplane building design.

The setup the. Superconducting machine relies on the cooling framework also. Basically on the cooling energy accessible. The world's aviation business need in length imagined from claiming hosting those methods for multi-year cryogenic cooling for space should empower long-life sensors of Different types to scientific, rocket resistance observations [18]. However, Eventually today standards, they would at present excessively awful overwhelming to utilization once aircraft [19]. Aerospace cryocooler are generally of very low power (W rather than kW). All currently known superconductors must operate at cryogenic temperatures between 4 and 80 K [16]. The technology of creating low temperatures is quite complex, and a great deal of ingenuity is required to build cooling equipment (called refrigerators or simply cryocooler) capable of achieving these low temperatures. The world's aerospace industry has long dreamed of having the means for multi-year cryogenic cooling in space to enable long-life sensors of various forms for scientific, missile defense observations. A superconducting magnet has to be cooled to a temperature suitable for its efficient and reliable operation. The simplest way of cooling a magnet is to bathe it in a pool of liquid cryogen, which boils at a temperature suitable for the superconductor materials. A cryogen boils at a constant temperature if it is maintained under a constant pressure [17]. The performance goals for aircraft set by NASA are very stringent, such as a 55 dB noise reduction, 75 % emission reduction, and a 70 % fuel burn reduction. Future system work based on numerical analysis of different heat exchanger types where high compressive efficiencies are likely [19].

1.7 Contribution of the research

The main contributions of this thesis are as follow:

- 1) Using Solid Work environment to completely design the aircraft body (Aurora D8) and analyzing it in ANSYS interface.
- 2) Transport current loss simulation and efficiency calculation of the racetrack armature coil in motor using COMSOL 5.3
- 3) Modelling of the cryocooler in ANSYS CFD

1.8 Thesis Organization

The rest of the dissertation is organized as follows:

Chapter 2: *Aircraft Configuration Analysis*

This chapter comprises of detailed explanations of the aircraft body configuration and its benefits. A simulation is carried out in ANSYS (simulation software) and the result is analysed..

Chapter 3: *HTS Motor & Simulation of HTS Racetrack Armature Coil Made Up Of YBCO Using COMSOL 5.3*

The following chapter contains the working principle of a HTS rotating machinery and the equation needed to calculate the transport current loss of the HTS racetrack coil of the machine. After that a 3D model of the racetrack coil will be designed in COMSOL 5.3 and simulation will also be carried out.

Chapter 4: *Cryocooler*

The whole chapter is based on the cooling system of HTS motor. First a brief description about different types of cryocooler, its liquid content (i.e. the liquid which will be used for cooling), the relation between its mass & temperature and finally its efficiency. The second part has the simulation process and its result.

Chapter 5: *FEA Software Simulation, Analysis and Comparison with MATLAB Results*

In this chapter, simulation results of different parts of the aircraft have been given which are using MATLAB and ANSYS Simulation. After that, the comparison between MATLAB and ANSYS simulation results will be analyzed. Finally, we will have the efficiency of the whole scenario that we tried to find out from our project.

Chapter 6: *Conclusions and Future Work*

In this last chapter the main results of this dissertation are summarized, and some concluding remarks and identify potential directions for future research have been given

Chapter 2

Aircraft Configuration Analysis

2.1 Aircraft Configuration Background

Over the past century, commercial airline operations has experienced only two fundamental transitions in aircraft configuration.

In 1935, the launch of the DC-3 by Douglas Aircraft was the first revolution. It had several new concepts in technology such as radial air cooled engines with cowlings, high-lift flaps, variable pitch propeller, light weight stressed skin structure and retractable landing gears. NACA (National Advisory Committee for Aeronautics), the predecessor of NASA, developed these technologies along with standardizing airfoil structures known as NACA airfoils.

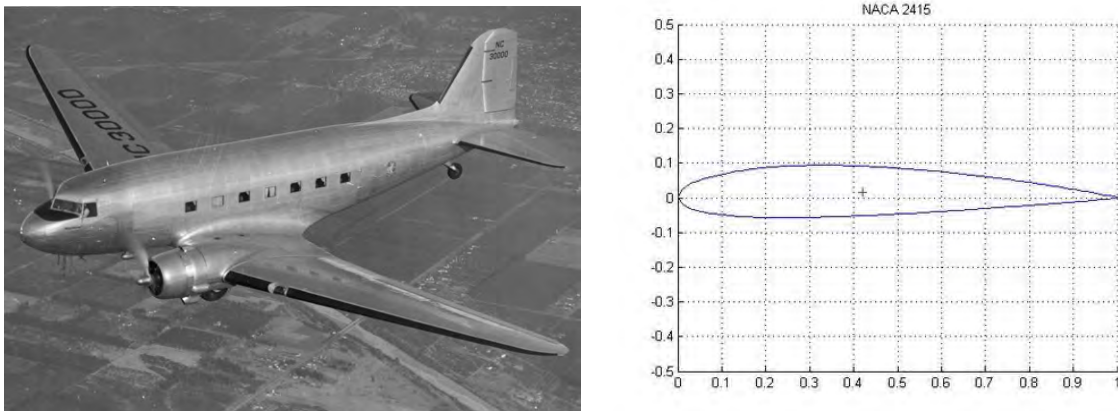


Fig: 2.1 DC-3 by Dauglas Aircraft (left); A sample of NACA airfoil (right).

The second revolution hit in the late 1950s, the evolution of jet aircrafts from propeller driver aircrafts. Boeing Commercial Aircrafts dominated the industry from then on.



Fig: 2.2 Great Britain's BOAC was the first to begin commercial jet aircraft operations, in May 1952.

Over the next 60 years, the commercial aircraft industry did not adopt any drastic modification of aircraft configuration. Although, the fuel efficiency has improved steadily through improvements of engines and propulsion systems rather than changes in configurations of the airframe.

The past 60 years the aircraft industry exhibited almost the same configuration of round tubular fuselage, fixed wing and nacelle under the wing. On the other hand engine configurations underwent several modifications, from turbojets, to turbofans, to high bypass ratio turbofans, to geared turbofans recently.



Fig: 2.3 A conventional aircraft.

This trend of engine upgrade, however, results in increased nacelle drag, increased propulsion weight and under-the wings installation challenges.

In recent times, under the initiation of NASA Aeronautics, teams if US government, academia and aeronautics industry is assertively pursuing conceptualization and development of new airframe architectures with potential for significant overall efficiency which is far beyond what is achievable through sub-system advances. Such configurations can achieve up to 70% of fuel savings compared to conventional commercial aircrafts. NASA developed few set of goals to be

achieved in near-term, mid-term and far-term, and is working on synergic models to achieve these goals. [1]

2.2 The Double Bubble D8 Concept, Design Features & Benefits

The concept of D8 originated from the N+3 Phase-I research of NASA, during which a team from MIT, Aurora Flight Sciences and Pratt & Whitney (P&W) conducted conceptual exchanges, framework and architectural trades and system modification to develop a theoretical conceptual design of an ultra-efficient 180-passenger transport aircraft. The objective of the NASA N+3 project was to develop a visionary aircraft that would extensively reduce fuel consumption, sound pollution and emission of greenhouse gases with a target to enter service around 2035.

The characteristic feature of the D8 is its twin aisle lifting body fuselage, low sweep wings and integrated Boundary Layer Ingesting (BLI) propulsion under the π -tail at the rear end. The configuration of the D8 alone provided majority of the improvements in efficiency and performance rather than any of the individual technologies integrated in to the aircraft. It's a revolutionary innovation from the NASA's N+3 project and signifies the importance and benefits of synergy in uplifting the overall efficiency of an aircraft and hat an evolution can occur on a much shorter period of time than that would take for individual system technologies to be more sophisticated eventually.



Fig: 2.4 D8.5, A modified version of D8 [2]

The D8 series has been designed in a newly developed tool ‘TASOPT’ – Transport Aircraft System Optimization that incorporates the design and optimization, airframe, aerodynamics, engine and operation parameters. This tool has the objectives within itself and checks whether the demands are being met and if not a design can be reinserted into the design loop to meet the goals. The software uses structural theory for primary structure sizing, weight prediction, viscous/inviscid fluids, CFD for various drag prediction and variable wing and tail airfoils, along with full engine flow-path simulation and variable flight trajectory. This helps in more accurate data prediction for this unconventional aircraft and minimum reliance on historical data for conventional aircrafts. [1] The aircraft is mainly compared to and targeted as a replacement of Boeing 737-800.

The D8 series aircraft is nicknamed ‘double bubble’ due to its identical fuselage compared to the conventional tubular ones and takes a converging form at the trailing edge known as the ‘beaver-tail’. The fuselage is flatter, a shape that is formed when two tubes are merged together side-wise. The nose of the aircraft is slightly lifted from the traditional nose. Instead of widely popular T-shaped tails the D8 series sports a pi-tail arrangement with integrated aft engine. The wing of D8 series are of very low sweep. This configuration of the aircraft provides more lift for

it than the convention ones. In this thesis a simulation will be done on ANSYS to study its relation between lift coefficient and angle of attack.

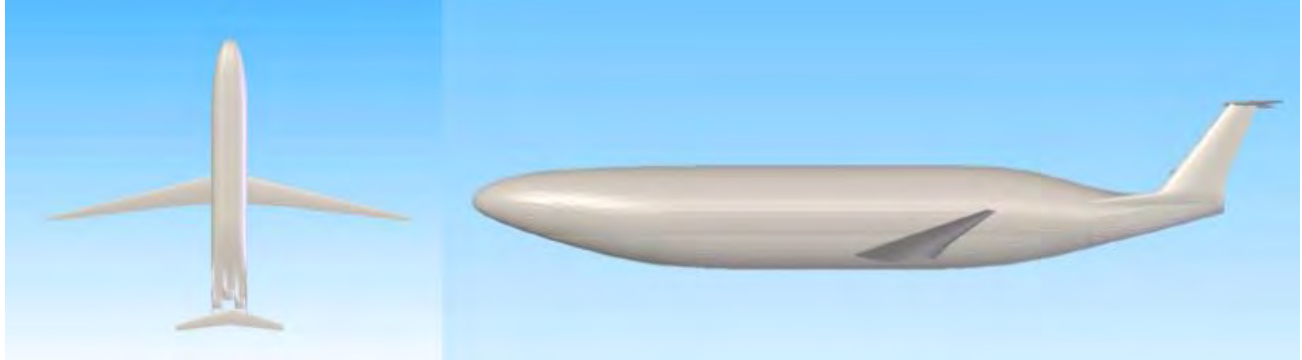


Fig: 2.5 Top-view and side-view of the D8.5 [2]

2.2.1 Design Features & Benefits[2]

- Double Bubble fuselage with lifting nose:
 - Increases maximum carryover lift and yielding span.
 - Produces lofted nose trimming moment through extra lift on the nose.
 - Provides wider cabin area compared to tubular fuselage.
 - Provides weight advantage.
 - Increases propulsive efficiency due to integrated Boundary Layer Ingestion (BLI) engines.
- Integrated Aft Engines:
 - Allows use of more efficient pi-tail.
 - Enables BLI.
 - Provides lower engine-out yaw.
 - Provides reduced risk of bird-strikes.
 - Enables reduced drag due to integrated nacelles rather than under-wing nacelles and fin strakes.

Other features:

- o Reduced Mach 0.74 (D8.5) with almost unswept wings vs Mach 0.80 and 25° of B737-800 reduces CDi (induced drag) due to unswept wings.
- o Unsweeping of wing increases CL_{max} .
- o The configuration makes best use of synergy in fin strakes by functioning as mounting pylons for engines and tail surfaces.
- o Reduces vulnerability of the engine fans by shielding it from ground observers.
- o Suffices smaller vertical pi-tails with less weight than T-tails.
- o Reduces wake vortex circulation by 80%.
- o Reduces engine noise by applying multisegment acoustic liners.

In addition to these, some advanced technologies has also been included in the D8.5 version:

- o Engines with ultra-high bypass ratio.
- o Advanced light weight structural materials.
- o Reduced structural load margin and gust load alleviation system.
- o Advanced engine components.
- o Advance engine functioning.

Metric	737-800 Baseline	N+3 Goals % of Baseline	D8.5
Fuel Burn (PFEL) [KJ/kg-km]	7.43	2.23 (70% reduction)	2.17 (70.87% reduction)
Noise [EPNdB] (EPNdB below Stage 4)	277	202 (-71 EPN dB)	213 (-60 EPNdB)
LTO NOx [g/kN] (% Below CAEP 6)	43.28 (31% below CAEP 6)	>75% reduction	10.5 (87.3% reduction)
Field Length [ft]	7680 ft for 3000 nm mission	5000 ft (metroplex)	5000 ft

Fig: 2.6 NASA N+3 Metrics and performance of D8.5[2]

2.3 Configuration Geometry & Dimension

The blueprint of our proposed model Aurora D8.5 is shown in figure 2.7. This blueprint is then inserted in solid works (see figure 2.8) and based on that the overall model is designed which is given in figure 2.9. The parameters which will be used for designing the model and for simulation are tabulated in table 2.1

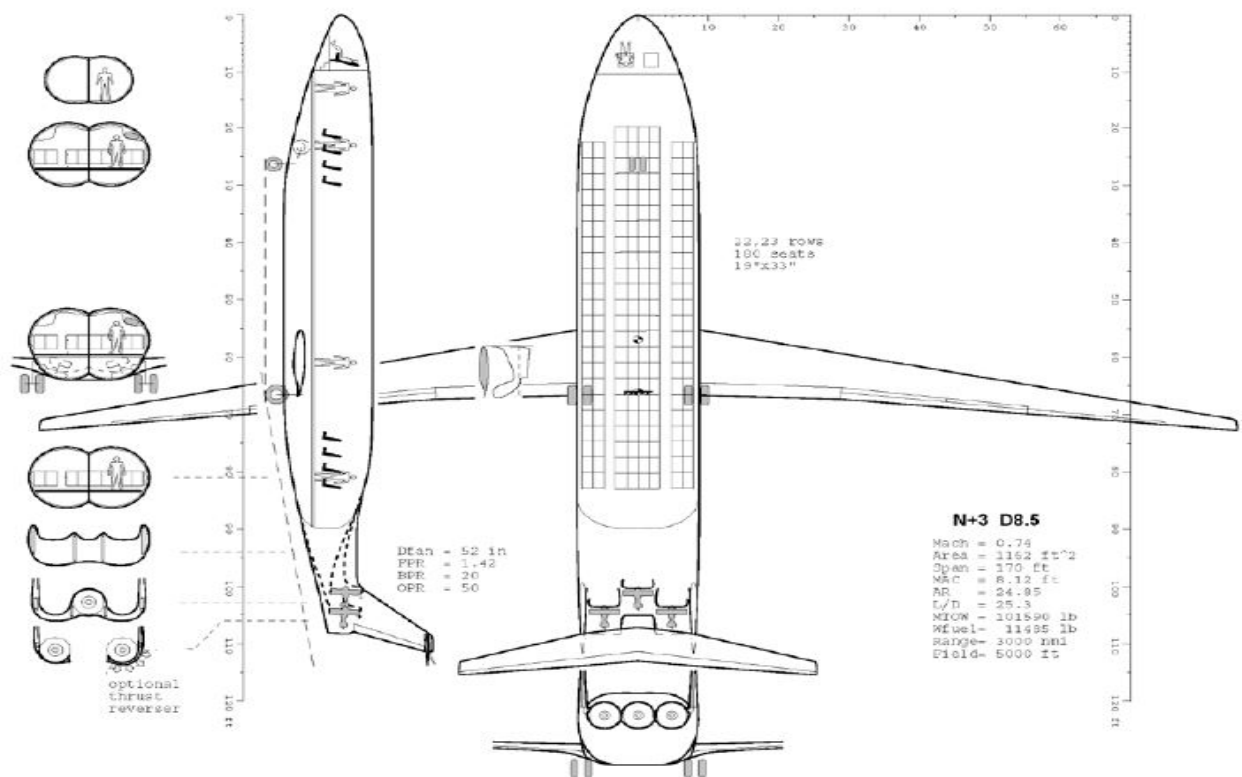


Fig: 2.7 D8.5 layout[2]

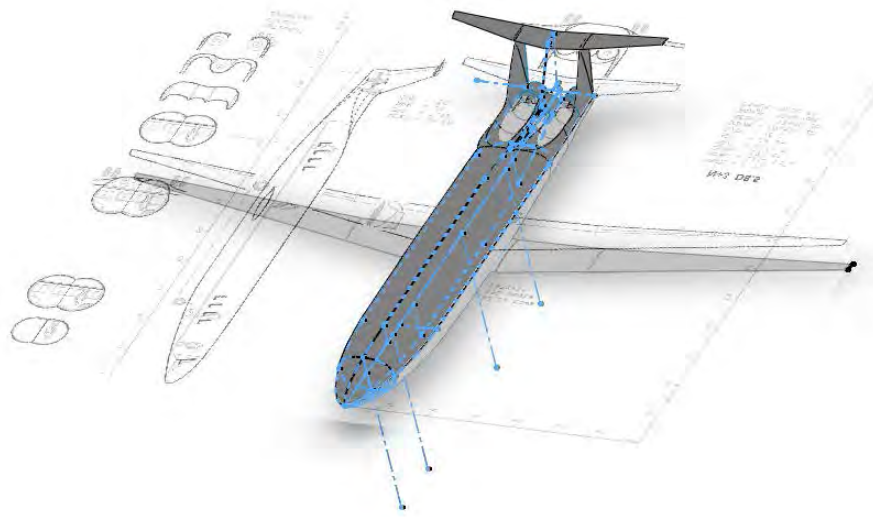


Fig: 2.8 Blueprint of D8.5 on Solidworks

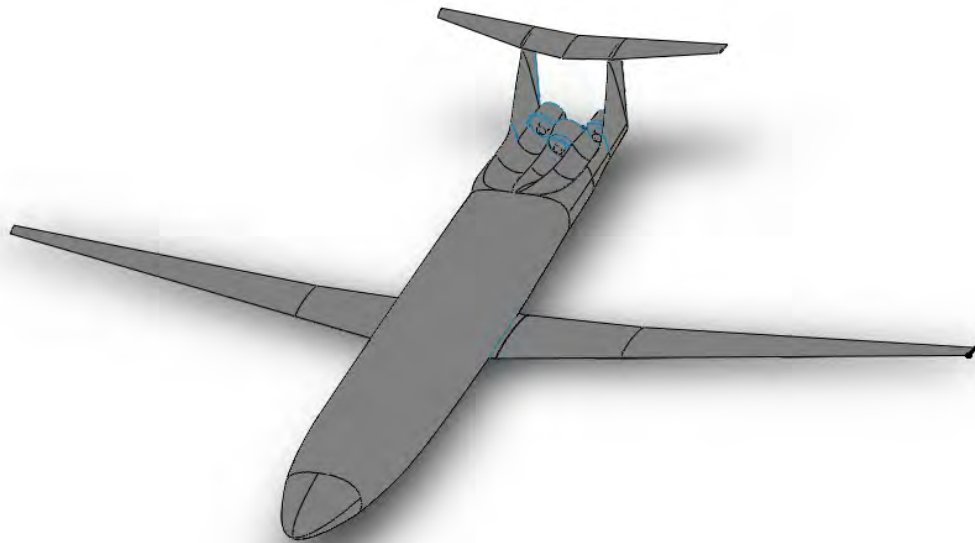


Fig: 2.9 D8.5 model designed in Solidworks

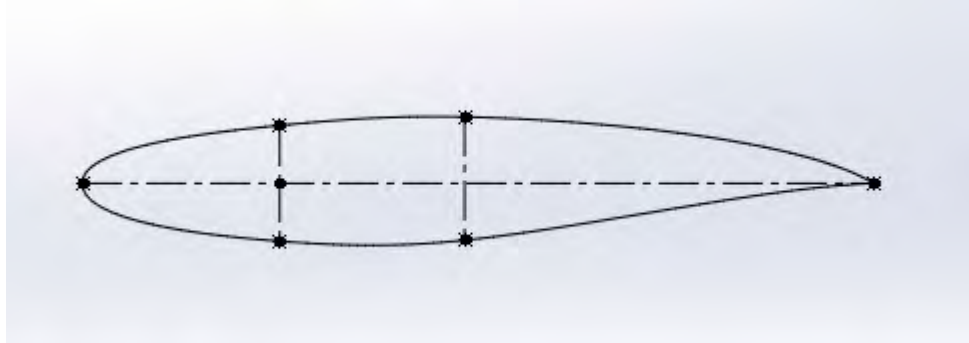


Fig: 2.10 Airfoil of D8

Mach	0.74
Span (feet)	170
Wing Area (sq. feet)	1162
Aspect Ratio, AR	24.85
Sweep (deg)	12.6
Cabin width (feet)	16.7
Cabin height (feet)	7.4
Fuselage width (feet)	17.4
Fuselage height (feet)	12.7
Fuselage length (feet)	107
Horizontal tail AR	13.0
Horizontal tail span (feet)	50

Table: 2.1 Aircraft parameters

2.4 Simulation & Results in CFD Solver, ANSYS Fluent

The simulation was done in the fluent module of ANSYS. There are different steps needed to be followed in order to do simulating in the software. In this case the geometry is designed in Solidworks which is then later uploaded in ANSYS.

1. Geometry
2. Mesh
3. Setup
4. Solution
5. Results

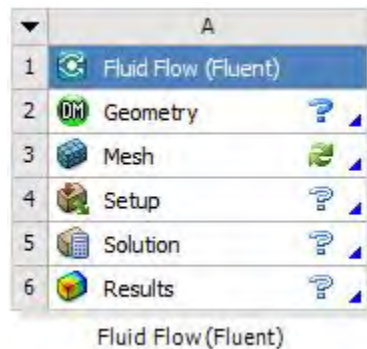


Fig: 2.11 fluent module of ANSYS

The purpose of the simulation was to find lift co-efficient, C_L for different angles of attacks, α . The lift coefficient, C_L is a dimensionless coefficient that relates the lift generated by a lifting body to the fluid density around the body, the fluid velocity and an associated reference area. C_L is often calculated with reference to an angle of attack, α .

Angle of attack (AOA or α) is the angle between a reference line on the body (often the chord line of an aero foil) and the vector representing the relative motion between the body and the fluid through which it is moving. Simply said, angle of attack is the angle between the body's reference line and the oncoming flow. The results is obtained by varying the component of forces in the setup section of the software (see figure 2.12).The results obtained are given in table 2.2 and 2.3.

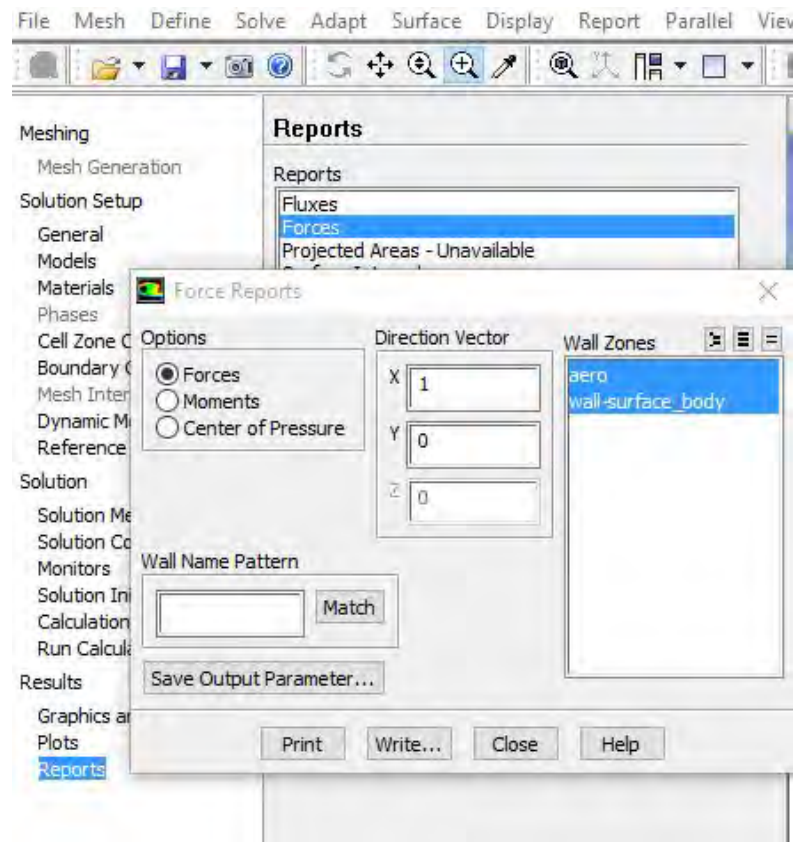


Fig: 2.12 Varying components of force

α	X(horizontal or cosine component)	Y(vertical or sine component)
0°	1	0
2°	0.9993	0.0349
4°	0.9975	0.06975
6°	0.9945	0.1045

Table: 2.3 Horizontal & Vertical components for different α .

α	C_L
0°	0.619
2°	0.749
4°	1.2261
6°	1.4643

Table: 2.3 Lift Co-efficient, C_L for different α (angles of attack)

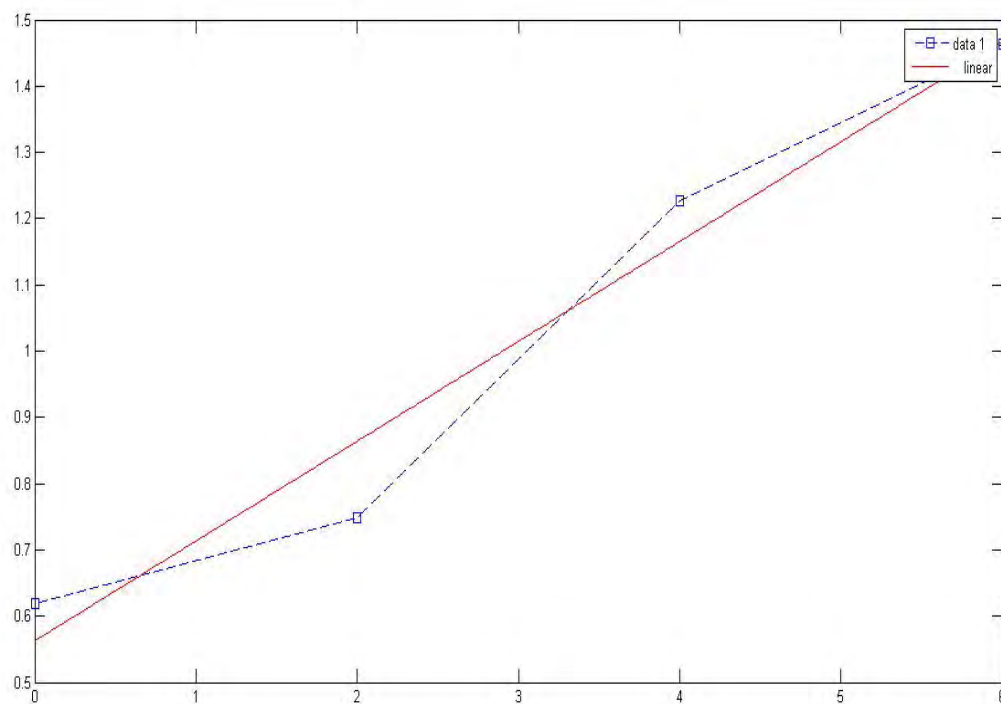


Fig: 2.13 Graph of C_L vs. α for Aurora D8.5

The above figure demonstrate how our simulated C_L value varies with α . The characteristic of a C_L vs. α plot is that with increase of the angle of attack the corresponding lift coefficient, C_L increases until a certain point after which it starts to decrease. The angle where C_L is maximum is called the stall angle. This graph, in most cases, has an intercept at Y- axis due to the fact that most aerofoils are positively cambered (more convex on the top surface than the bottom). The overall analysis of this results and the theoretical value will be further discussed in chapter 5.

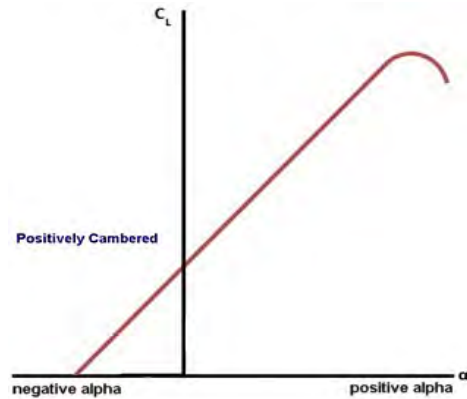


Fig: 2.14 Typical C_L vs. α plot for a positively cambered aerofoil

2.5 Summary

Electric aircrafts implies not just replacing conventional combustion engines and mechanical sub-systems with electric, motor driven engines and smarter, more automatic electric systems, rather it focuses on the aircraft as a whole and especially on the airframe structure for it vitally affects the overall efficiency of the aircraft.

Chapter 3

HTS Motor & Simulation Of HTS Racetrack Armature Coil Made Up Of YBCO Using COMSOL 5.3

3.1 Introduction

The use of high temperature superconductors in practical electrical machines has been impeded to a limited extent by the low critical current densities and sensitivity to magnetic field, which is quite normal in these machine. In this chapter we study this phenomenon by simulating the transport loss in a HTS racetrack coil and calculating its efficiency. By comparing the simulated results with the theoretical value our coil model is validated for its use in the HTS motor which in turn will be used in the electric aircraft. This chapter first discuss the type, the manufacturing process of HTS wire and the various type of losses in HTS wire. The second part is about the coil design and modelling procedure. The last section is about the efficiency of the coil.

3.2 HTS Material (YBCO)

HTS (High Temperature Superconductor) are layered materials mainly composed by copper oxide planes, called Perovskites, which have been found with T_c of more than 100 K. HTS are by and large defined as superconductors with a T_c higher than around 23 - 30 K (30 K is as far as

possible permitted by BCS hypothesis, 23 K is the 1973 record that kept going until copper-oxide materials were found [11]).

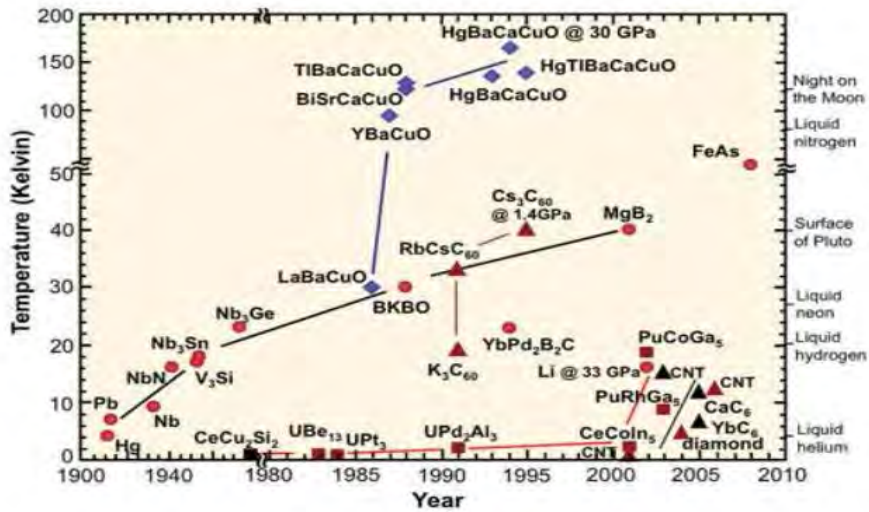


Fig: 3.1 Critical temperatures and year of discovery for different superconductors [11]

Yttrium Barium Copper Oxide YBCO ($\text{YBa}_2\text{Cu}_3\text{O}_7$) is the most well-known of these HTS material and was found by Paul C. W. Chu and M-K. Wu in 1986 and 1987[11], individually, and is known as the second generation (2G) HTS - the second HTS to be utilized for making conducting wires. It was the first material to show superconductivity at temperature over 77 K, the boiling point of liquid nitrogen, and has thus made broader possibilities for practical application. Every single other material found before this showed superconducting characteristic at temperatures close to the boiling point of liquid helium or hydrogen (4.2 K and 20 K, respectively). This was a significant achievement since nitrogen is the most plenteous component in the environment and it is inexpensive. Also, liquid nitrogen based cryocooler are reliable and have been normally used in many industries. One advantage of YBCO is that it is the cleanest and most ordered crystal - the crystalline structure of YBCOs is given in fig 3.2. According to this figure the base left are the axes (or planes) of the material. The structure of YBCO is very anisotropic, with considerably higher conductivity inside the CuO_2 than perpendicular to the planes. In this manner, supercurrents flow just within the CuO_2 (a-b) planes, i.e. left to right in the figure, which means the trapped field created by these supercurrents is coordinated along the c-axis [11].

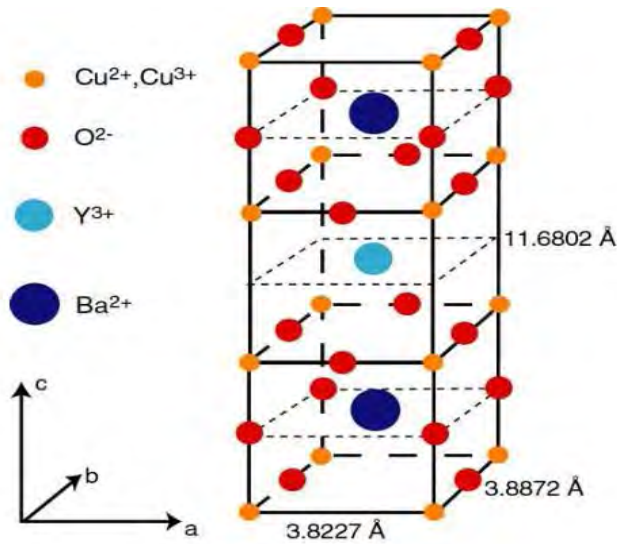


Fig: 3.2 crystalline structure of YBCO [11]

Another plus point of YBCO wire is its capacity to stay at superconducting state with current densities (J_c) more noteworthy than 10^3 A/mm² in fields up to a few Tesla. The properties of YBCO was compared with other HTS material like BSCCO wires and the analyzed result is shown in in figure 3.3 [10]. From the figure, it might be seen that the performance of the wires increment significantly with the decrease of temperature.

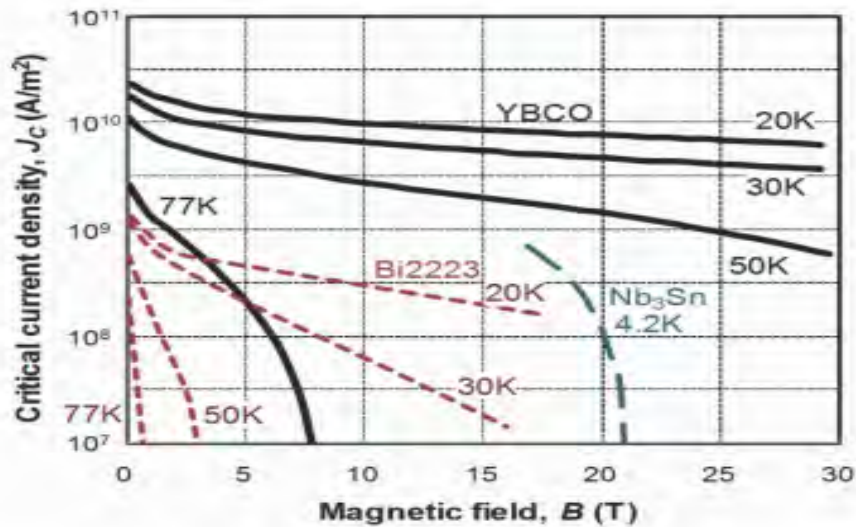


Fig: 3.3 Performance comparison of YBCO and Bi-2223 superconducting wires at various temperature and magnetic field [10]

3.2.1 Commercial HTS wire

There are two organizations that supply long lengths of YBCO-based HTS tape/wire: American Superconductor (AMSC) [12] and SuperPower [13]. The fabricating strategies differ between the two, which brings about a different configuration for the final product. In recent years long lengths of wire has been accessible commercially, which has made it conceivable to wind coils for motor application.

AMSC's manufacturing procedure of YBCO-based HTS wire is focused on the RABiTS/MOD (rolling assisted biaxially textured substrate/metalorganic deposition) technology and an outline of this innovation is shown in figure 3.4. The buffer layers (a 75 nm Y₂O₃ seed layer, a 75 nm YSZ barrier layer and a 75 nm CeO₂ cap layer) are stored onto a metal alloy (Ni-W) substrate through the process of high rate reactive sputtering and the rare earth doped YBCO is coated onto the buffered substrate [11]. The YBCO is topped with an Ag layer, after that oxygenated, and overlaid between two metallic stabilizer strips, which can be either brass or copper.

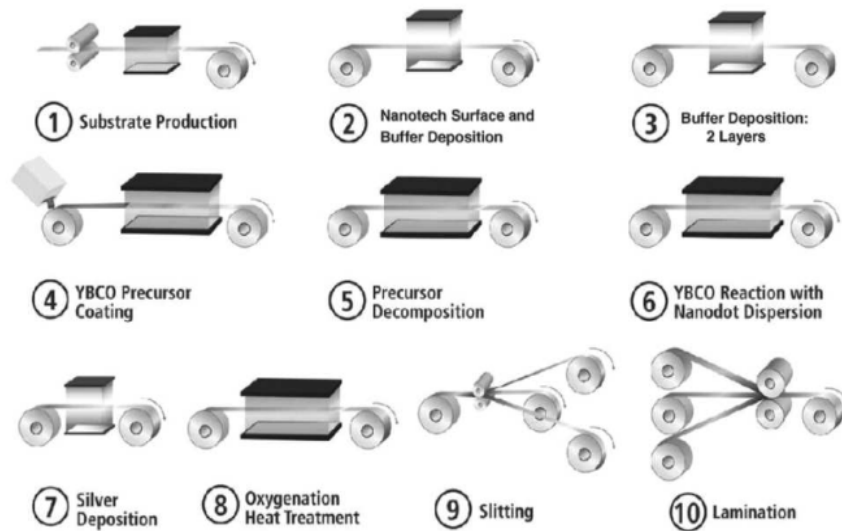


Fig: 3.4 Overview of AMSC HTS wire manufacturing process [11]

SuperPower's approach depends on the IBAD/MOCVD (ion beam assisted deposition/metal organic chemical vapor deposition) technology, which includes sputtering a heap of buffer layers to introduce the biaxial texture for the YBCO layer, which is deposited using MOCVD method. A thin strip of silver is then sputtered to give electrical contact. Based on the application, this is then electroplated in order to completely surround the wire. The configuration of SuperPower's YBCO-based HTS wire is appeared in Fig 3.5

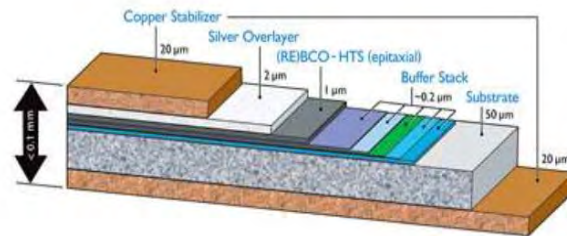


Fig: 3.5 SuperPower HTS wire configuration [11]

3.3 Application of HTS in electric machine & motor working principal

In general electric machine like motor and generator have copper winding in its stator and rotor. Current flowing through these wires creates resistive loss and its one of the main issue for the delay in development of electric planes. According to the design in [22] a 10MW motor is needed to run an aircraft. At this rated power the size and the losses increases and is becomes economically unsustainable to run planes with normal conventional motor. This problem is solved by replacing normal motors with HTS motors. The design and parameters of such 1MW motor is given [14]. For our aircraft aurora D8, 10 of these kind of motors are used to run the turbine of the plane. The reason for choosing HTS motor is due to their high efficiency (which will be calculated later in this chapter) and compact size.

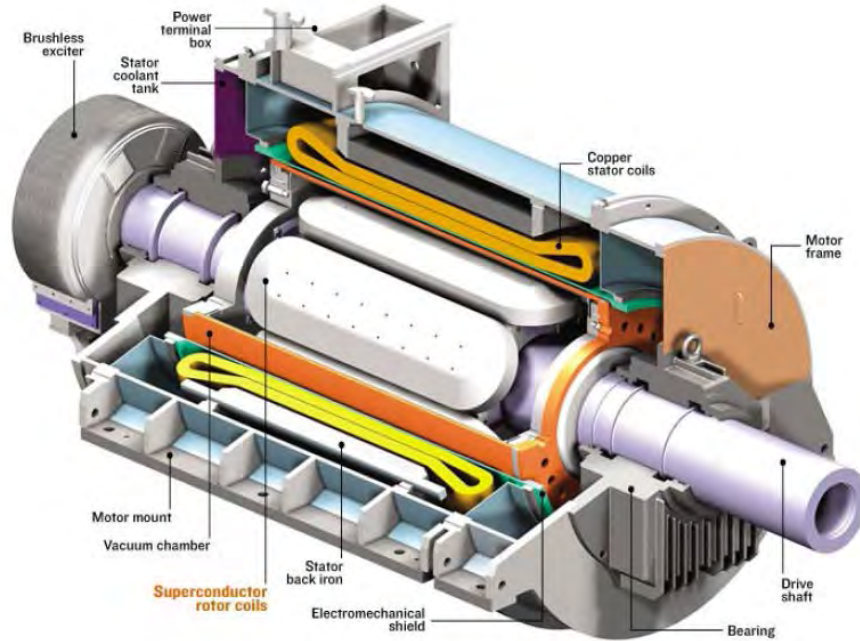


Fig: 3.6 AC synchronous machine with YBCO winding [9]

Fig 3.6 shows the overall structure of a HTS motor. A magnetic field is produced by the rotating HTS field winding in the armature. The strength of this field is normally twice that of a regular motor [9]. The HTS motor rotor is composed of an air core (i.e. nonmagnetic) and non-metallic teeth in the stator, which enable the air-core field to be enhanced without the core loss and saturation problems inborn in laminated iron stator and rotor core. The position of HTS armature winding is outside the air core and in a few applications it is installed in nonmetallic teeth to give mechanical support.

In steady state condition, the rotor turns in sync with the rotating magnetic field due to the three phase armature currents, and the superconducting field winding encounters just DC magnetic fields. However under load condition, the rotor moves regarding the armature created fields, and it experiences AC field harmonics.

An electromagnetic (EM) shield situated between the HTS coils and the stator winding shields the HTS field winding from these AC fields. A warm (room temperature) EM shield is situated at the external most surface of the rotor. Inside the warm shield is a thermal insulation (vacuum) that encompasses the rotor cryostat. The cold EM shield (if employed) is within surface of this

vacuum space and is a high - conductivity shell close to the working temperature of the superconducting coils. The superconducting field coils are situated inside the inward EM shield on a nonmagnetic support structure. The warm EM shield, which transfers torque to the warm shaft, is intended to be mechanically robust to withstand the large force produced during faults, and is intended to absorb heating caused by negative currents and other harmonic currents. A refrigeration cooling system is used, which utilizes liquid nitrogen gas (or other appropriate gas), and keeps the HTS material at cryogenic temperature. The overall design and analysis of this cryogenic (cooling system) is discussed in chapter 4.

3.4 Losses in HTS coil

A superconductor does not incur any loss in its superconducting state as it provides no electrical resistance. Be that as it may, it stays substantial when the superconductor isn't presented to magnetic fields over its lower critical field. If the connected magnetic field (H) surpasses H_c , which is normally the case in large electrical machine, the superconductor no longer remain lossless. At low frequencies, typical of electrical power applications, resistance emerges in type II superconductors as a result of flux flow and flux creep [11]. Type II superconductors are of substantially more technological interest since they can convey more current and larger magnetic field so it can be used for larger electrical power machine like motors. However, type II superconductors have losses since electric fields can be produced inside. This AC losses can be divided into two classifications:

- 1) Magnetization loss
- 2) Transport current losses.

3.4.1 Magnetization loss

It is the power dispersed in the superconductor when an alternating magnetic field which is produced by the AC transport current, B , is applied to the superconductor. In case of time varying external magnetic field the loss occurs because of hysteresis and coupling currents. There are three sorts of losses that make up the magnetization loss:

A) Hysteresis loss

B) Coupling loss

C) Eddy current losses.

A) Hysteresis losses: Hysteresis losses are a consequence of irreversibility caused by vortex pinning [11]. These losses are called hysteresis losses because of the fact that the flux that has entered the superconductor does not leave exactly in a similar way by which it entered due to this pinning. In the event that one plots the magnetic induction, B , versus the magnetic field, H , a hysteresis loop is acquired, which is traversed once per cycle [11]. The energy loss per cycle is directly proportional to the area of this loop. Such hysteresis losses are disseminated as heat and its much higher for stronger pinning; subsequently, larger critical current of a HTS material means the hysteretic loss will be high. An example of a hysteresis (or magnetization) loop is shown in Fig 3.7.

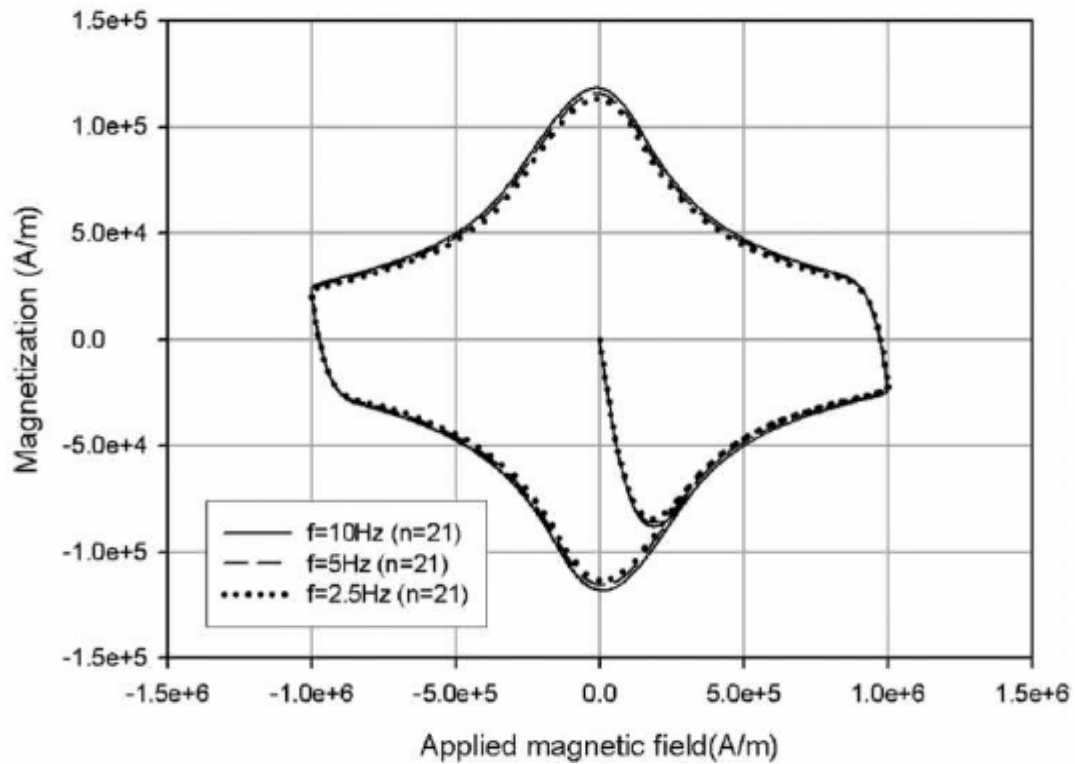


Fig: 3.7 Magnetization loop for a full cycle of applied field [11]

B) Coupling losses: Coupling losses can be a significant issue in multifilamentary conductors, for example, BSCCO (Bi-Sr-Ca-Cu-O), which comprises of various superconducting filaments inside a silver sheath. It can likewise be an issue in YBCO conductors if the tapes are striated into filaments. An eddy current initiated by a fluctuating magnetic field, flows partly through the superconductor and furthermore through the silver between the filaments. As current flow from one filament to other, they can couple the filaments together into a solitary large magnetic system, which experiences a resistance along the current path.

C) Eddy current loss: When an external time-varying magnetic field enters into an ordinary conductor, it instigates a changing electric field, which in turn causes current to flow. These are known as eddy currents. Because of this eddy current in the tape, the ohmic energy dissemination can be significant if the magnetic field is opposite to the tape.

3.4.2 Transport current loss

A transport current in a superconductor produces a magnetic field around the conductor, which is known as the self-field. With alternating transport current, the rotating self-field infiltrates the superconductor during every current cycle. Transport current loss can be categorized into two type of losses.

A) Hysteresis loss

B) Flux Flow Loss

A) Hysteresis losses: When there is an alternating transport current flowing through the superconductor, a hysteresis losses (like that portrayed above for magnetization losses) happens. The self-field of the superconductor act as applied filed, and the energy of the self-field must be provided by the source of the transport current.

B) Flux flow loss: As transport current builds up, more and more flux lines are depinned and will move in the superconductor. The vitality scattered related with this procedure is called flux flow loss. Initially, the self-field loss dominates, yet with increasing transport current, the flux flow loss becomes prominent.

One of the main objective of this thesis is to calculate the transport current loss in the coil of the motor and calculate the overall efficiency. In order to do that, it is quite essential to predict the electromagnetic behavior and of the superconductors. The difficulty in evaluating the quantitative electromagnetic properties of HTS materials is significantly increased because unlike normal conductors like copper they are characterized by a highly non-linear current-voltage relationship. The next section will first describe the structure of the coil that is being considered for the HTS motor and the simulation step to see how the magnetic flux density and current

density changes with time. The simulation and calculation of the transport current loss and its efficiency is done in the following chapter.

3.5 HTS Racetrack Coil 3D modelling in COMSOL 5.3 & AC Loss Calculation

The coil design is based on the 1MW propulsion motor for electrical aircraft as shown in Fig.3.8. The synchronous engine has four poles so its speed is 1500 rpm with 50 Hz armature excitation. The parameters specification of the motor is given in table 3.1. The turbofan of the aircraft will be replaced by this motor by being equipped and associated with a fan to propel the aircraft. The rotor is made of permanent magnets and the armature has six 2G HTS racetrack coils. The rotor is made up of iron excluding the shaft and stator support. The block diagram of the overall HTS system which will be used to power the aircraft is given in figure 3.9.

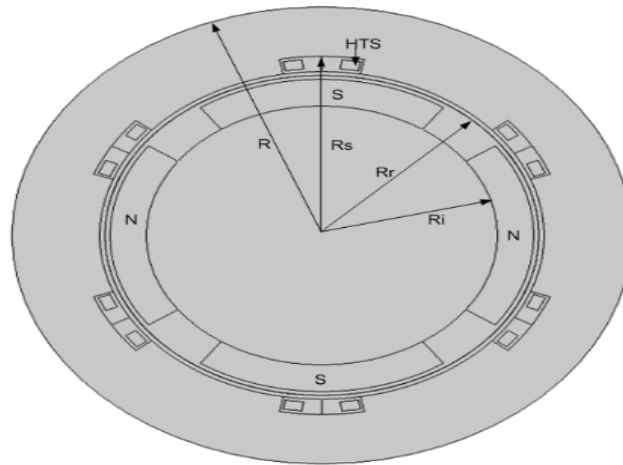


Fig: 3.8 1MW Propulsion Motor [14]

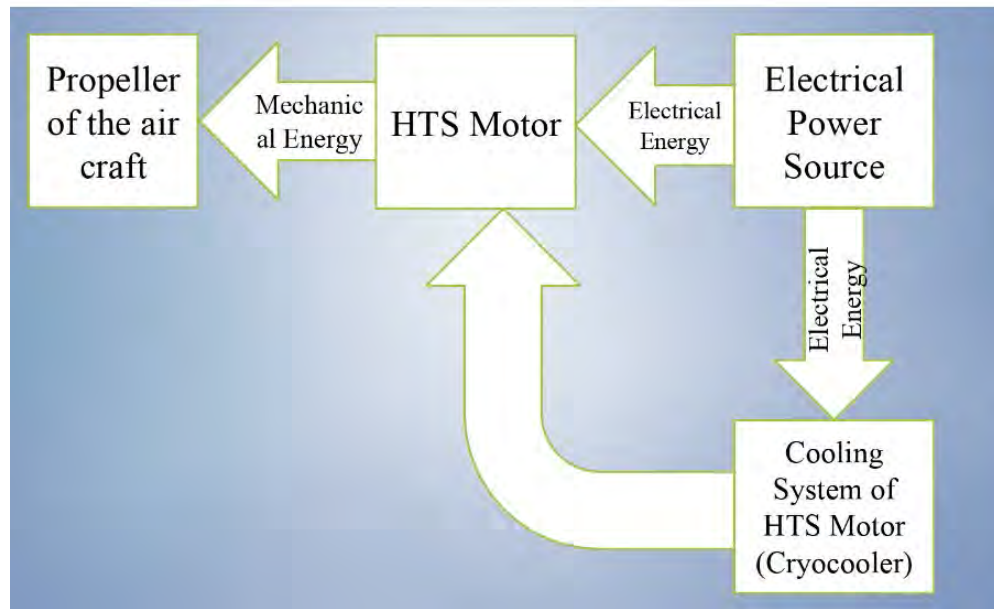


Fig: 3.9Block diagram of the HTS system

Symbol	Meaning	Value
P	Machine power	1MW
L	Machine length	0.63m
σ	Sheer stress	32kPa
R_r	Air gap radius	0.215m
R_s	Outer slot radius	0.23m
R	Outer machine radius	0.32m
P	Pole pair	2
Ω	Machine speed	1500 rpm

Table: 3.1 1MW Propulsion Motor Design Parameters [14]

Table 3.2 demonstrates the plan of 2G HTS racetrack coil design [14] and these parameters are inserted in COMSOL and the resultant 3D design is given in fig 3.10. The computational time required to do simulation on these 3d model is quite large. So to save time a simulation is done for the cross section area of the 2d model in order to find out how the magnetic flux density and

the current density varies with time. The cross section area of the coil which will be used for the simulation is given in fig 3.11.

Symbol	Meaning	Value
N	Total turns	$39 \times 2 = 72$
R₁	Inner diameter	0.2 m
R₂	Outer diameter	0.216 m
H	Thickness	0.01 m
T	Tape length per coil	254 m

Table: 3.2 Racetrack Coil Parameters

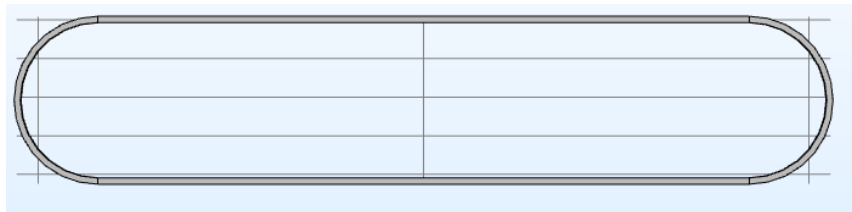


Fig: 3.10a 2D Racetrack Model

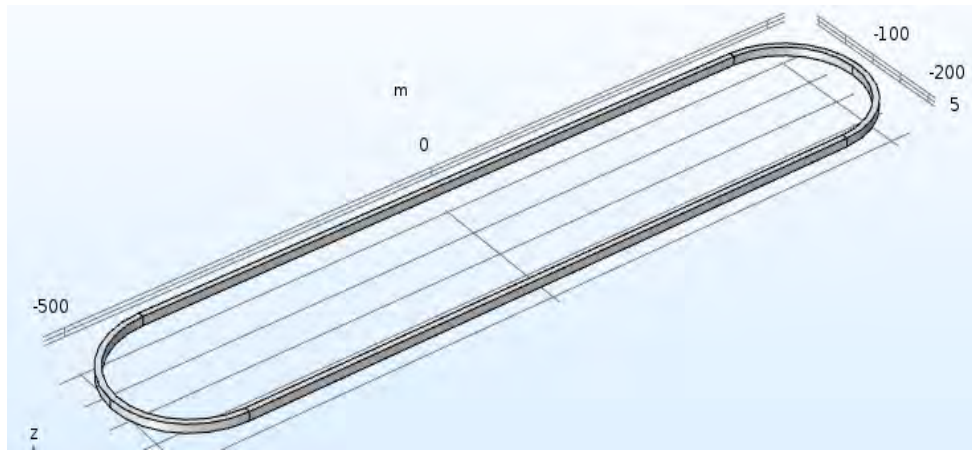


Fig: 3.10b 3D Racetrack Model

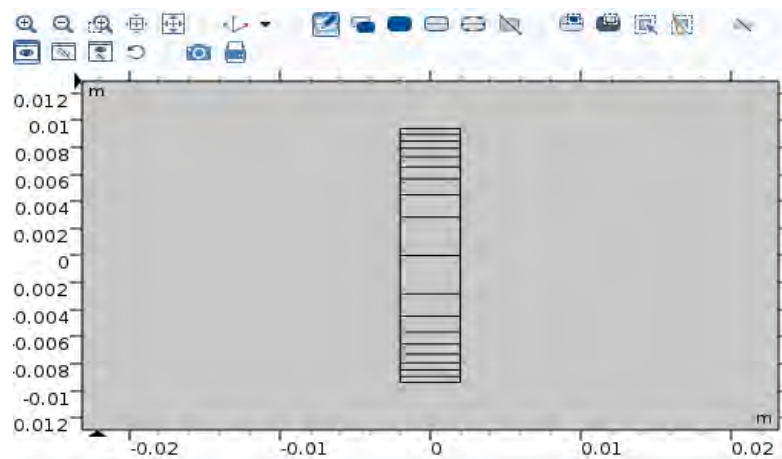


Fig: 3.11 Cross Section Area of racetrack model

To calculate the loss we are using Kim model [9] to model the change of electromagnetic behavior of the coil. According to these model the critical current density J_c is dependent on temperature and magnetic field. The magnetic dependency is only considered for our model

keeping the temperature constant i.e heat production generated by loss is equal to the heat removed by the cryocooler. The $J_c(B)$ equation of the super conductor tape is given by equation 3.1

$$J_c(B) = \frac{J_{c0}}{1 + \frac{B_y}{B_0}}$$

Where $J_{c0} = 17MA$ and $B_0 = 0.23$ [14]. This is only the y dependency of the critical current density and the x dependency is given by equation 3.2. Equation 3.3 shows the overall dependency $J_c(B_y, B_x)$. This equation is inserted in comsol as an analytic function and the graph generated is given in fig 3.13. More detail about the use of analytic function in comsol can be found in [20].

$$J_c(B) = \frac{J_{c0}}{1 + \frac{B_x}{B_0}}$$

$$J_c(|B_x|, |B_y|) = \frac{J_{c0}}{1 + \frac{\sqrt{K^2|B_x|^2 + |B_y|^2}}{B_0}}$$

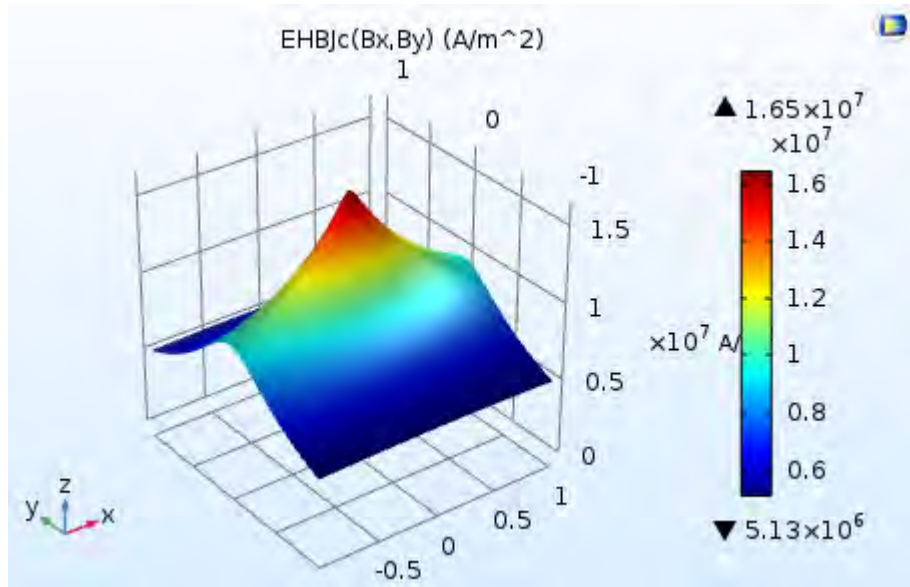
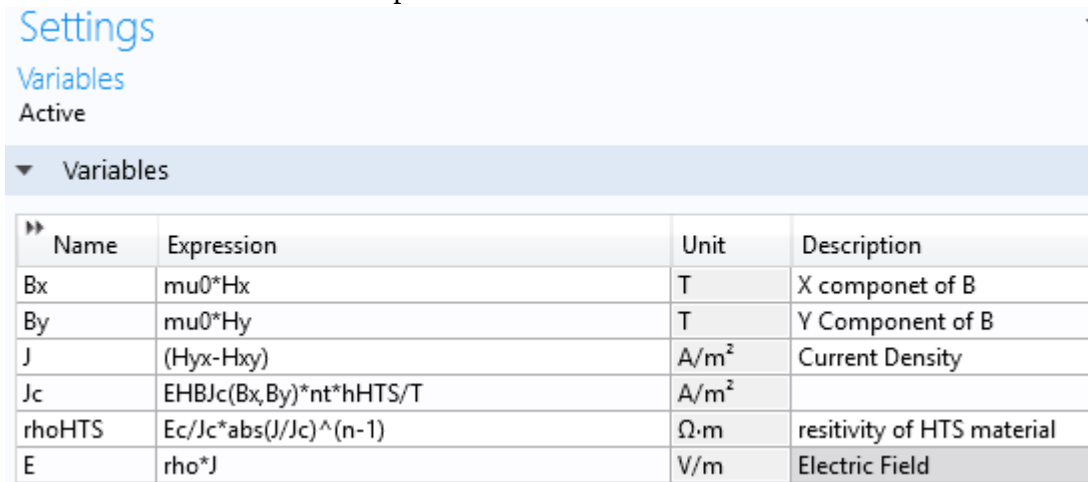


Fig: 3.12 Overall dependency of $J_c(B_y, B_x)$

Here in equation 3.3 the parameter $K = 0.29515$ and $|B_x|$ and $|B_y|$ are the perpendicular components of the magnetic flux density which are calculated from equation 3.1 and 3.2. As stated earlier HTS material does not have a linear I-V graph. According to the literature [15], the resistivity of HTS material is model by power law dependency of critical current density which is given by the equation 3.4.

$$\rho_{HTS} = \frac{E_c}{J_c} \left| \frac{J}{J_c} \right|^{n-1}$$

The value of $E_c = 100 \mu V/m$ and n is the anisotropic property of YBCO whose value is 38 [15]. Using the PDF physics of comsol and the H formulation values of H_x and H_y are calculated. The y and x component of magnetic flux density are calculated using $B = \mu H$ where μ is the free space permeability. All these calculation are made using comsol by inserting all these as variables and table 3.3 shows these inputs.



The screenshot shows the 'Settings' window in COMSOL Multiphysics, specifically the 'Variables' section. It contains a table with the following data:

Name	Expression	Unit	Description
Bx	$\mu_0 H_x$	T	X componet of B
By	$\mu_0 H_y$	T	Y Component of B
J	$(H_{yx} - H_{xy})$	A/m ²	Current Density
Jc	$E_H B J_c(B_x, B_y) \cdot n \cdot h_{HTS} / T$	A/m ²	
rhoHTS	$E_c / J_c \cdot \text{abs}(J / J_c)^{(n-1)}$	$\Omega \cdot m$	resitivity of HTS material
E	$\rho \cdot J$	V/m	Electric Field

Table: 3.3 Variables for calculating the parameters for loss

Finally, in order to calculate the instantaneous loss (W/m/s) the surface integration formula in [15] is used and is given in equation 3.5.

$$Q = \int_S E \cdot J \, ds$$

Ac current is supplied through the coil so calculate the average loss over a period can be derived from the following equation. In our calculation an 50Hz ac supply is used so the simulation result are over a single period and is given in fig 3.14. The overall efficiency of the motor and the validation of the result will be discussed in the next section.

$$\xi = \frac{1}{T} \int_T^{2T} dt \int_S E \cdot J ds$$

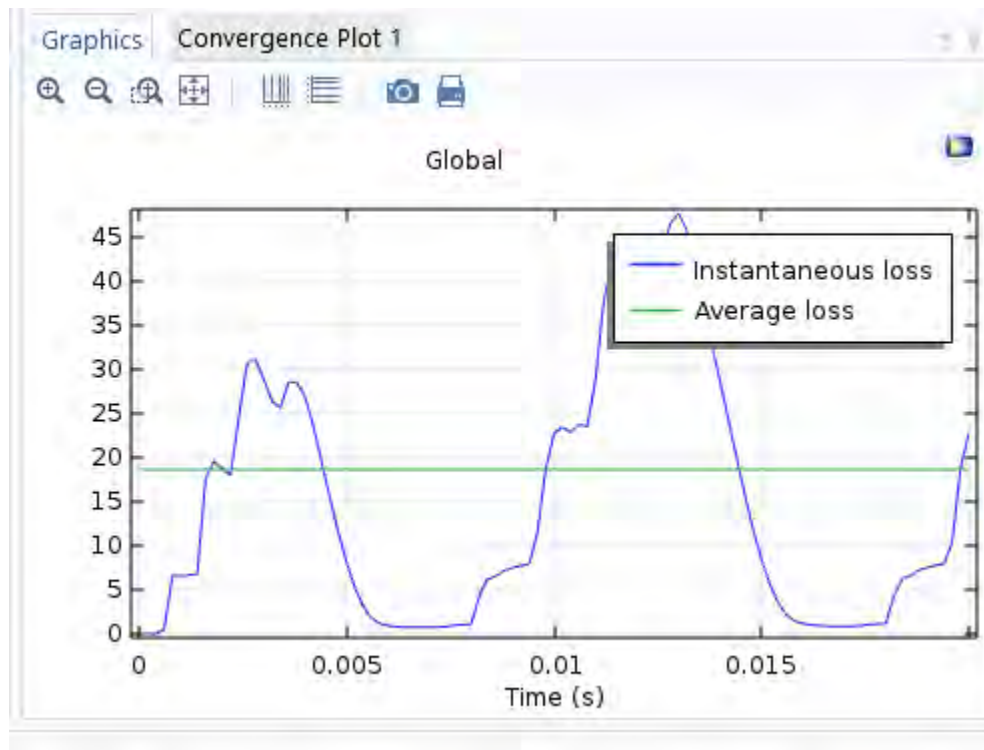


Fig: 3.13 Instantaneous and average loss of a racetrack coil of 1MW motor

The above figure shows the loss at an input current of 72A. Now same simulation is done with different current and these current values are taken from [14]

3.6 Result Analysis

After carrying out the simulation in comsol the average loss for 72 tapes of HTS coil is found out to be 18.648 J/m. The overall length of a HTS tapes required to make a single racetrack coil for our 1MW motor is 254m which is given in table 3.2. Therefore the loss in a single coil is 28419.552J. The overall efficiency of the motor which is using six of these coil is

$$\eta = \frac{(1 \times 10^6) - (6 \times 28419.552)}{(1 \times 10^6)} \times 100 = 97.1 \%$$

In the literature [14] the overall efficiency of the whole motor is 98% which is derived by carrying physical experiment of the motor. The reason for this difference is due to the fact that in our calculation the temperature is considered constant, however the J_c of HTS material is depends both on temperature and the change of magnetic flux density. The simulation computational time also depends on the number of tapes. Higher number of turns means the results will be more accurate but the time taken to get this results will be large. So to compensate between accuracy and simulation time 72 tapes were chosen. Moreover, the efficiency that we have calculated is within the range for a motor to drive an electric aircraft. The figure 3.13 shows the loss of a motor having a ratings of 1MW and a current of 72A. Now same simulation is done with motor with dofferent power ratings. The ratings are 1.25MW and 1.5MW and the currents are 90A and 108A respectively and their efficiency is calculated. The simulated results are given in table 3.4 and the loss graph are demonstrated in figure 3.14 and 3.15. The magnetic flux density variation of the coil and the reason behind to choose YBCO as our HTS material will be investigated in chapter 5. The percentage difference with the therotical value is calculated in chapter 5.

Power	Input current in one coil	Number of tapes/coil	Magnetic field (T)	Average loss (J/m)	Total loss (J)	efficiency
1MW	72	72	0.67	18.648	28419.552	97.1
1.25MW	90	72	0.67	37.717	57028.104	95.43
1.5MW	108	72	0.67	68.056	102900.672	93.13

Table: 3.4 Tabulated simulated results for different motor

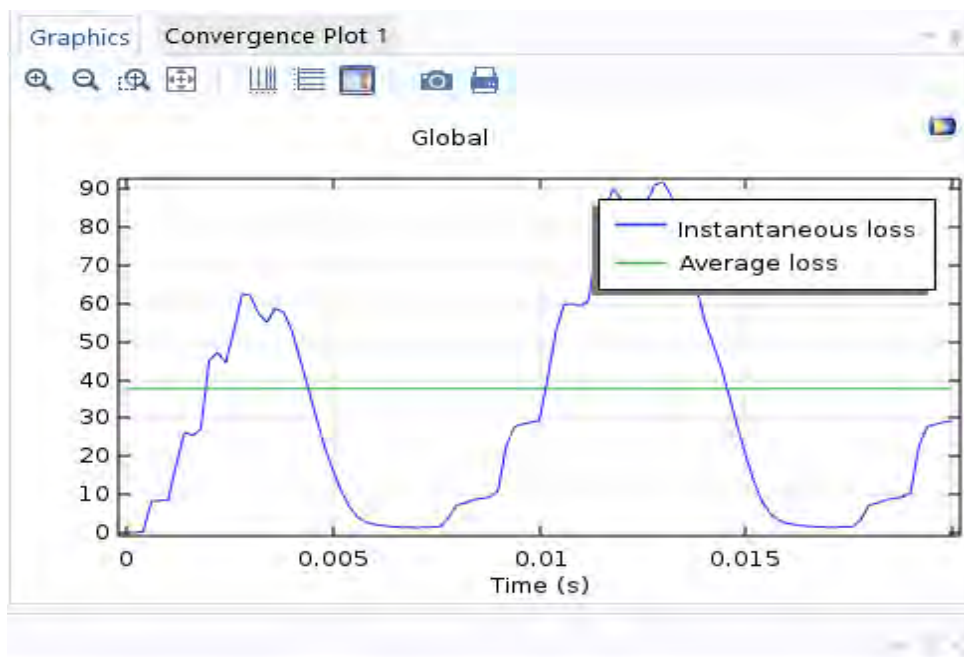


Fig: 3.14 Instantaneous and average loss of a racetrack coil of 1.25MW motor

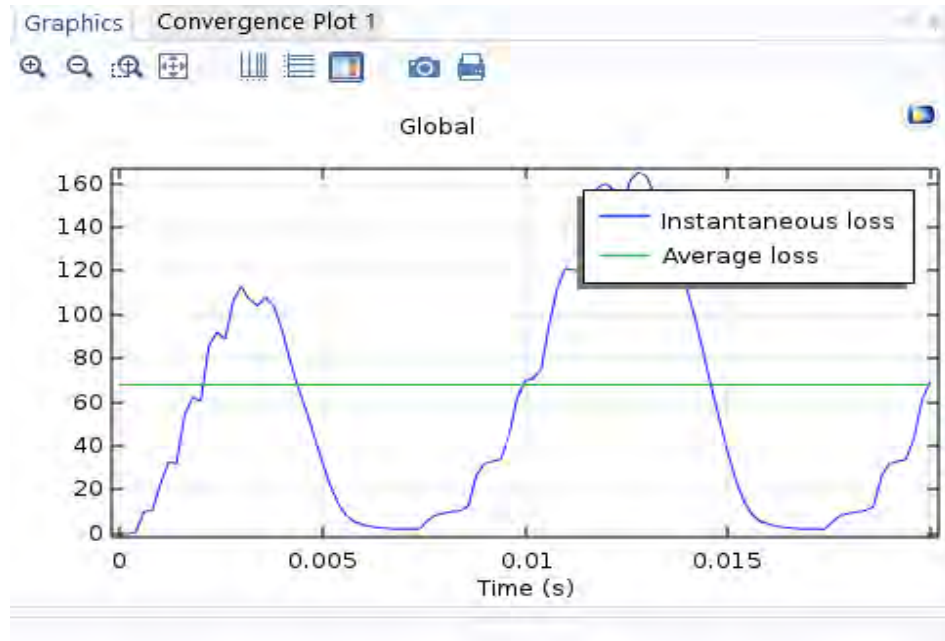


Fig: 3.15 Instantaneous and average loss of a racetrack coil of 1.5MW motor

3.7 Summary

In this chapter, the procedure of simulating AC losses in superconducting racetrack coils, with a particular focus on the transport AC loss of coils for electric machines (1MW propulsion motor), is addressed. Then the efficiency of this machine is compared with the theoretical value in [14]. The simulation was done in COMSOL 5.3 and moreover the results is further validated by doing two more simulation and calculating the efficiency of 1.25MW and 1.5MW propulsion motor.

CHAPTER 4

Cooling System of HTS Motor Using Cryocooler

4.1 Introduction

Cryogenics is the branch of studies which concentrate on physical wonders that happens at low temperature, hypothetically at a temperature of 0 kelvin. All as of now known superconductors must work at cryogenic temperatures in the vicinity of 4 and 80 K. The innovation of making low temperatures is very complicated, and a lot of resourcefulness is required to construct cooling machinery (called iceboxes or just cryocooler) equipped for accomplishing these low temperatures.. This is used in many application where the operating temperature is very low such as in the case of HTS motor. So content in this section are limited to types of cryocooler, the principal behind stirlingcryocooler and later a simulation is carried out to determine the effect of efficiency by changing various liquid.

4.2 Types of Cryocooler

We can characterize cryocooler based on its operating cycle and heat exchanger. On the basis of operating cycle it can be further divided into two groups

- 1) Open Cycle cryocooler
- 2) Closed Cycle cryocooler

Open Cycle cryocooler: These type of cryocooler utilize cryogenic liquids which are in liquid form either in subcritical or supercritical state and furthermore solid cryogenes are stored at high pressure.

Closed Cycle cryocooler: Refrigeration effect of closed cycle cryocooler is seen at low temperatures and it reject heat at high temperatures. They are basically mechanical cryocooler. Some example of this type of cryocooler are like Brayton cycle cryocooler, Stirlingcryocooler, Joule-Thomson cryocooler and so on. These closed cycle cryocooler utilizes two working liquids, one which will work in the cycle and the other one which will come in direct contact of the space to be cooled [50]

When heat exchange is taken into account this can be classified into two categories

- 1) Recuperative Cryocooler
- 2) Regenerative Cryocooler

4.2.1 Recuperative Cryocooler

Recuperative type cryocooler incorporates the Joule Thomson cryocooler and Braytoncryocooler [23]. The second incorporates the Stirling type and Gifford-McMahon composecryocooler. Details about all these four cryocooler will be discussed in upcoming sections

In recuperative cryocooler the flow of stream of the working liquid is unique, these are like direct current electrical frameworks. In order to maintain the flow direction the compressor and expander have isolate inlet and outlet valves. Valves are vital when the system has any revolving or turbine components. In rotary motion of components there are greatest chance for reverse flow of the working fluid, so to avoid this from happening valves are essential [41]. These working liquid are fundamental components of the cycle so that is the reason for the proficiency of the cryocooler to depend on it. One of the main advantage of recuperative cryocooler is that it can scaled to any size for the desired output. They are grouped into valve less and with valves kind of cryocooler [50]. Few example are given in fig 4.1. Large quantity of working liquids can be utilized as a part of these frameworks in light of steady pressure oscillations; thus these liquids flows anyplace with the exception of areas where there are larger radiation heat leaks because of extra volumes at the cold end. Because of expansion and cooling of the working liquid inside the cryocooler, there is a possibilities of “pipe cold “at different parts. As the cool end of the cryocooler is isolated from the compressor part, vibration of compressor is reduced incredibly.

As the space between cold space and compressor part of cryocooler is large so electromagnetic interference is additionally reduced.

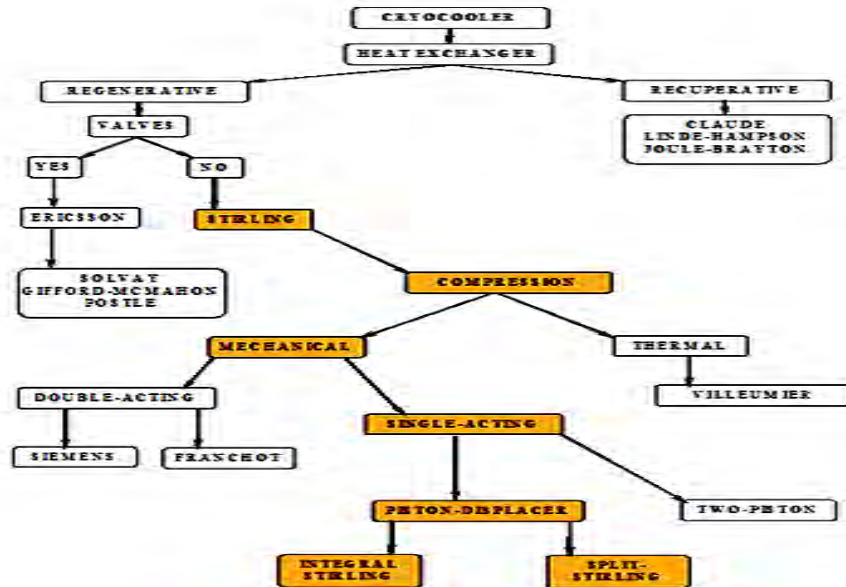


Fig: 4.1 Classification of cryocoolers[24]

4.2.2 Regenerative Cryocooler

These cryocooler are like alternate current electrical system since the working liquid oscillates in the flow channel .In other words there is oscillatory movement of the working liquid inside these sort of cryocooler in which it oscillates in cycles and while moving through the regenerator part of the cryocooler and it exchange heat with the wire mesh. The heat capacity of the regenerator is quite high, which stores the heat for one half of the cycle and for the other half it gives it back to the working fluid. These are extremely efficient due to their low heat exchange loss yet these cryocooler can't be scaled up to large sizes which is one of its drawbacks. There are mass flows and oscillating pressures in the cold head and there is a phase relationship between the mass

streams and the weight varieties. The oscillating pressures can be created with a valve less compressor as appeared in figure 4.2

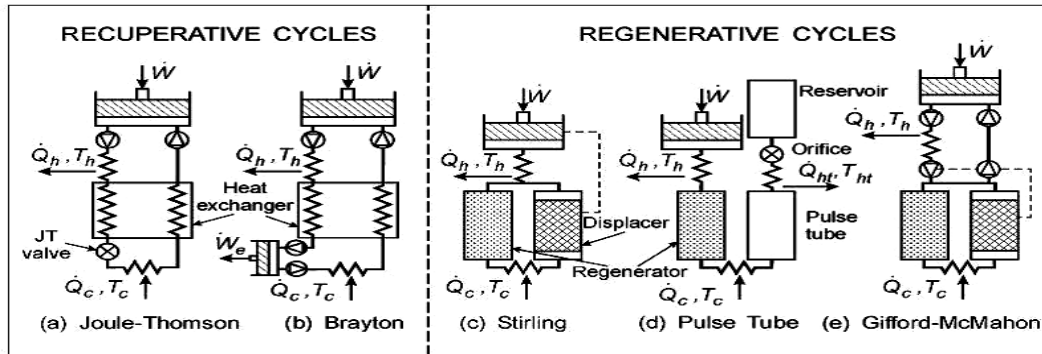


Fig: 4.2 Different types of cryocoolers[24]

Some example of cryocooler which are used in industries and for electric machinery are

- 1) The Joule-Thomson cryocooler
- 2) BraytonCryocooler
- 3) Pulse Tube Cryocooler
- 4) Stirlingcryocooler

All of these cryocooler are discussed below and by comparing them our desired cryocooler model will be chosen. In the next section the design will be done in ANSYS and later the simulation results will be discussed in section 4.3.

4.2.2.1 The Joule-Thomson Cryocooler

The Joule-Thomson cryocooler working principal is based on the expansion of gases from high pressure to low pressure. The development occurs with no generation of work or heat input, thus, the procedure happens at a constant enthalpy. The heat input occurs after the expansion and is used to evaporate any fluid formed in the expansion procedure or to warm up the cold gas. For a ideal gas, enthalpy is independent of pressure given that temperature remains constant but its changes with pressure for ral gas. In this manner, cooling in a Joule-Thomson cryocooler expansion only occurs for real gases and at a temperatures which is below the inversion curve. At low temperatures the cooling increases for a given pressure change and it is greatest close to the critical point. Usually argon and nitrogen are used as a part of joule Thomson cryocooler and

to get a decent cooling effect, 20 MPa pressure or more than that is utilized on the high pressure side. As Joule Thomson cryocooler doesn't contain any moving parts a very high cooling rate is achieved. When Joule Thomson cryocooler works in an open cycle mode it goes on for few days just till the gas evaporates completely from it and in the heat exchanger small scale finned tubing is utilized. Through an explosive valve Gas streams from the high pressure bottle and afterward it gets out to the atmosphere. In case of closed cycle mode, its efficiency decreases because of the clogging by moisture at the little opening. Nowadays, JT cryocooler are used with blends of various gases as its working liquid. This blend of gases brings down the freezing point of liquid as a whole by having gases with higher boiling points.

4.2.2.2 BraytonCryocooler

Another name of these type of cryocooler is reversed Brayton cycle as cooling happens by the expansion of gas and in this procedure it works. The total heat retained with an ideal gas in the Brayton cycle is equivalent to the total work produced which is as indicated by the First Law of Thermodynamics. This procedure is then much more effective than the Joule Thomson cycle and it does not require high pressure ratio. These Cryocooler are generally used in large liquefaction plants. If the operating temperature is over 35 K, Neon is generally used as the working fluid, however for lower temperatures helium is utilized. BraytonCryocoolerare having low vibration of their rotating parts in a framework with centrifugal compressors and turbo expanders.

4.2.2.3 Pulse Tube Cryocooler

In a pulse tube cryocooler there is an appropriate gas movement in phase with the pressure which is accomplished by the utilization of an inertance tube alongside a supply volume or an opening to store the gas during a first half cycle. During the oscillation flow, the reservoir volume reduces any pressure motions which isolate heating and cooling effect. For a given frequency there is a limit on the width of the pulse tube in order to keep up adiabatic process. The operation cycle of this cryocooler is made up of four steps in the initial step the cylinder moves down to compress the gas in the pulse tube. Then in the second step this heated gas because of its higher pressure, it moves into the reservoir and exchange heat with the surrounding through the heat exchanger. In the third step then cylinder moves up and expands the gas adiabatically in the pulse tube. Finally, in the last step this low pressure cold gas is pushed through the cool heat exchanger by the gas from the reservoir and this stop when the pressure in the reservoir increments to the average pressure. The approaching high pressure gas is cooled by Regenerator before it reaches to the cold end. The gas in the middle of the pulse tube protects the two ends as it makes a temperature inclination between these two ends and never leaves its position. The turbulence is limited by the gas in between two ends. Pulse tube transfer an acoustic power in a oscillating gas system from one end to other over a temperature slope with least entropy generation and power dissipation. If any distinctive changes are made in geometries of pulse tube cryocooler then it increases the lower temperature limit.

4.2.2.4 Stirling Cryocooler

This is a regenerator type cryocooler and basically it has three configuration. These are alpha, beta and gamma type and all of these cryocooler operation works on Stirling cycle. Helium is utilized as the working liquid in engine. A perfect Stirling cycle which occurs in anticlockwise direction comprises of two constant volume process and isothermal process alternatively. The steady volume process are of heat addition and rejection while isothermal procedures are of

contraction and expansion. The general schematic of this cryocooler is given in figure 4.3 and the thermodynamic process involved is given in figure 4.4.

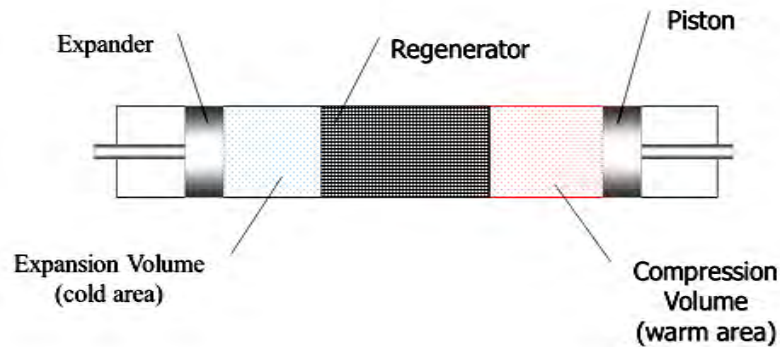


Fig: 4.3 Schematic representation of cryocoolers[24]

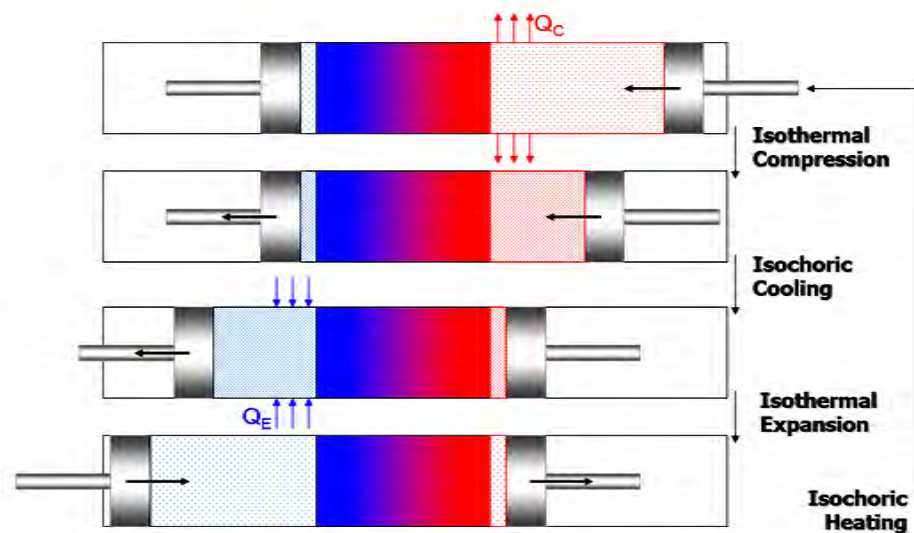


Fig: 4.4 Systematic representation of thermodynamic process involved in ideal Stirling cycle [24]

4.3 Transformation Process of StirlingCryocooler

The transformation process of Stirlingcryocooler is composed of three process:

1. Thermodynamic Process
2. Working Process
3. Cooling cycle

4.3.1 Thermodynamic Process

In accordance to the fig 4.4 the thermodynamic cycle can be divided into four parts.

- 1) **Isothermal Expansion:** Expansion occurs as the gas in cold heat exchanger travels through the regenerator towards the cold end at a constant temperature. Amid this procedure the liquid exchange heat with the regenerator as it gives away its warmth to regenerator to store it.
- 2) **Isochoric Heat Addition:** It is the part where the cooling effect is produced, the cold end is presented to the space so in this stage gas absorbs heat far from the space by keeping the volume of the cold space consistent.
- 3) **Isothermal Compression:** The gas from the cold end is packed and after that it goes through the regenerator at constant temperature towards the hot end of the cryocooler, amid its course it takes away heat which was put away in the regenerator.
- 4) **Isochoric heat dismissal:** The gas in the hot end is now having the heat from the regenerator and the space to be cooled. The gas is now in a compressed state which rejects heat to the encompassing space by keeping the volume of the cold space constant.

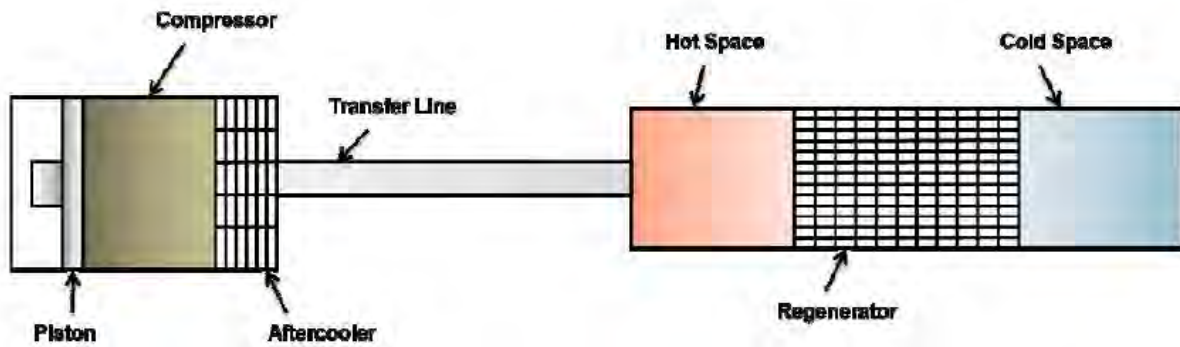


Fig: 4.5 StirlingCryocooler with schematic representation[24]

4.3.2 Working Process

From above figure 4.5 of Stirling cycle if the gas is at the greatest volume condition, at that point the gas retains heat from the space to be cooled while regenerator stays stationary and cylinder was moving towards left. Following stage the displacer moves to right and forces the liquid to go through it and while moving it absorbs heat from the regenerator at steady volume condition. Next the piston packs the working fluid as it moves right and this pressure at the hot end is isothermal so heat is emitted to the surroundings at the atmospheric temperature. Now the regenerator moves to left along these lines constraining the liquid to go through it and amid this the fluid gives away heat to the regenerator. It additionally keeps up consistent volume condition and this is an isochoric heat dismissal process. Next the piston moves towards left and in this manner making the liquid expand. A pressure oscillation in the framework will make temperature to fluctuate and produce no refrigeration. The nature of motion for the two sections are sinusoidal and displacer movement is 90 degrees out of phase from that of cylinder movement. With this condition the mass flow or volume flow through the regenerator is in phase of pressure [50]. The moving cylinder causes both pressure and development of the gas and net power Input which is required to work the framework. The moving regenerator reversibly extracts net-work from the gas at the cool end and transmits it to the heat end where it

contributes some to the compression work. In a perfect system, with isothermal expansion and pressure and a perfect regenerator, the procedure is reversible [50].

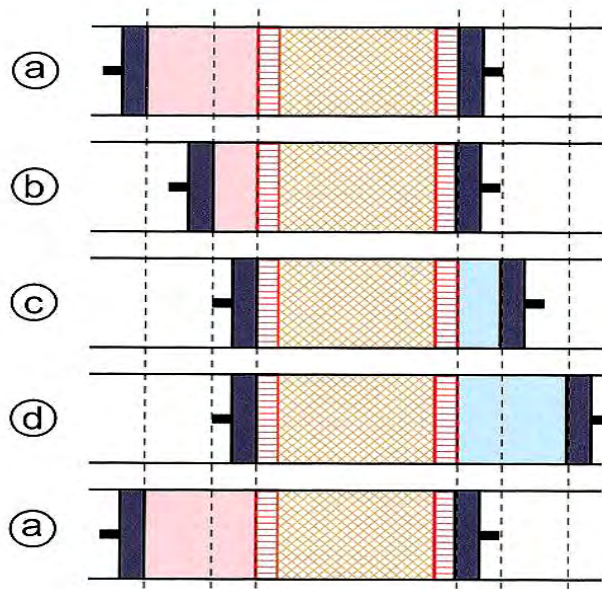


Fig: 4.6 Four steps involved in cooling cycle [24]

4.3.3 Cooling Cycle

The cooling cycle is part in four stages as appeared in Fig.8. At the point when the two cylinders are in their most left positions, the cycle begins:

- From a to b: The warm cylinder moves to one side while the cold cylinder is remain fixed. Isothermal compression is utilized at the hot end, so warm Q_a is radiated to the surroundings at ambient temperature T_a .
- From b to c: The two cylinders move to right while volume between the two cylinders are in steady condition. The hot gas enters the displacer with temperature T_a and abandons it with temperature T_L . The gas emits heats to the regenerator material.
- From c to d: The cold cylinder moves to one right while the warm cylinder is fixed. The extension is isothermal and warm Q_L is taken up. This is the useful cooling power.

- From d to a: The two cylinders move to left with isochoric process. The gas enters the displacer with low temperature T_L and abandons it with high temperature T_a so heat is taken up from the displacer material and the condition of the cooler is the same as in the beginning.

The relation between Q_a (heat being rejected from the compressor) during isothermal compression, and W_c (the work input) which is equal to Q_a [26] is represented in equation 4.1

$$Q_a = mRT_a \ln \left(\frac{V_{max}}{V_{min}} \right) = W_c$$

Here

$T_a = \text{ambient temperature}$

$V_{max} \& V_{min} = \text{Maximum and minimum volume}$

Heat absorbed in the expander during isothermal expansion is given by equation

$$Q_L = mRT_L \ln \left(\frac{V_{max}}{V_{min}} \right) = W_L$$

Hence the efficiency is given by equation 4.2

$$\eta = \frac{Q_a}{W} = \frac{Q_a}{W_c - W_L}$$

$$\eta = \frac{T_L}{T_L - T_C}$$

4.4 Analysis & Working Process of BraytonCryocooler

By comparing all the above discussed cryocooler, Braytoncryocooler is chosen as our cooling system of HTS motor. This chapter emphasizes on the overall structure of this cryocooler and the equation needed for simulation. Thermodynamic outline of Braytoncryocooler is presented as a major aspect of a ongoing Project. A continuous sub cooling liquid nitrogen from 72K to 65K is needed for this design. A perfect Brayton cycle for this application is first researched to inspect the fundamental highlights. After that a more practical approach is taken by designing the practical cycle for a Braytoncryocooler is composed, considering the performance of, expander, and heat exchangers. For simulation commercial software like ANSYS is utilized for mimicking the cycle with real fluid properties of refrigerant. Helium is chosen as a refrigerant, as it has a better thermodynamic efficiency than neon.

4.4.2 Thermodynamics Relation of BraytonCryocooler

This thermodynamic investigation displays the design specification and data for 10 kW Braytoncryocooler. The plan incorporates the choice of refrigerant and the working condition for high efficiency and the rand reliability the objective of refrigeration is to continuously sub-cool a liquid-nitrogen (LN) flow From 72 K to 65 K at a rate of 10 kW. The mass stream rate (m_{LN}) of fluid nitrogen is given by equation 4.2

$$m_{LN} = \frac{Q_{LN}}{C_{LN}(T_i - T_e)} = 0.710kg/s$$

Here

m_{LN} = mass stream rate ; T_i = inlet temperature (72K); T_e = exit temperature (65K)
 C_{LN} = specific heat of nitrogen ; Q_{LN} = heat absorbed by liquid nitrogen

The schematic diagram of heat exchanger is given in fig 5.111. In order for the combined energy and entropy to balance an absolute minimum work (W_{min}) must exits for this refrigeration, and

this is the difference of flow availability (energy) of liquid nitrogen between the inlet and exit [35]. Equation 4.3 defines this work and is given below

$$W_{min} = m_{LN} \times C_{LN} \left[(T_e - T_i) - T_H \ln \frac{T_e}{T_i} \right] = 33.8 kW$$

Here

T_H = ambient temperature (300K in this study)

Ambient temperature is the temperature at which heat is rejected by cryocooler. Figure of merit or FOM is another dimensionless thermodynamic parameter which is used to evaluate the performance of refrigeration and is as the ratio of minimum work to actual work [34].

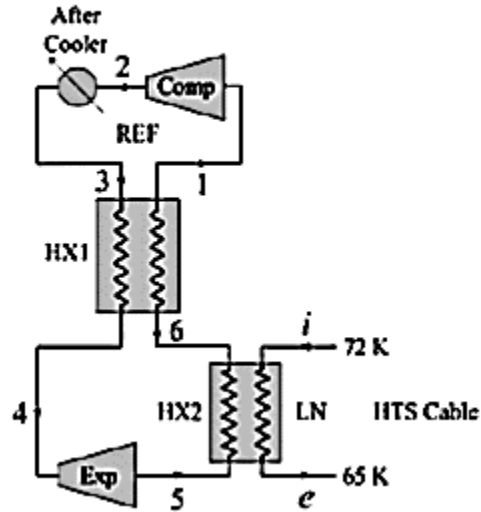


Fig: 4.7 Brayton cryocooler with counter flow heat exchanger (HX2) for cooling liquid nitrogen[(LN)[34]

$$FOM = \frac{W_{min}}{W} = \frac{W_{min}}{W_{comp} - W_{exp}}$$

As it was stated earlier that before practical design an ideal design will be considered. The basic concept of brayton refrigeration is given in figure 4.7. A standard reverse Brayton cycle consists of two isentropic process (compression and expansion) and two isobaric forms (heat

exchangers). It is expected that the refrigerant (helium or neon) is an ideal gas having constant specific heat [34].

Beside the inlet (i) and exit (e) temperature of LN, there are seven unknown parameters needs to be determined. These are pressure ratio($r_p = \frac{P_H}{P_L}$), flow rate of refrigerant () and refrigerant temperature (at 1, 2, 4, 5, 6). In case for ideal case only the pressure ratio is considered because a different choice of P_H and P_L with same pressure ratio results in exactly the same cycle [34]. The equation for energy balance for regenerative heat exchange (HX1) and LN heat exchanger (HX2) are given below (equation 4.4 & equation 4.5):

$$T_1 - T_6 = T_3 - T_4$$

$$m_R C_p (T_6 - T_5) = m_{LN}$$

Here C_p is the specific heat at constant pressure of refrigerant. The isotopic relations for compressor and expander are given by equation 4.6.

$$\frac{T_2}{T_1} = \frac{T_4}{T_5} = r_p^{(k-1)/k}$$

Here k is specific heat ratio of refrigerant and its value is 1.667 both for helium and neon. The performance of heat exchanger is given as a value of effectiveness. For HX1:

$$\varepsilon_{HX1} = \frac{T_1 - T_6}{T_3 - T_6}$$

Since the capacity rate is same for two streams. For HX2, however its:

$$\varepsilon_{HX2} = \frac{T_i - T_e}{T_i - T_5} (case I) \quad or \quad \varepsilon_{HX2} = \frac{T_6 - T_5}{T_i - T_5} (case II)$$

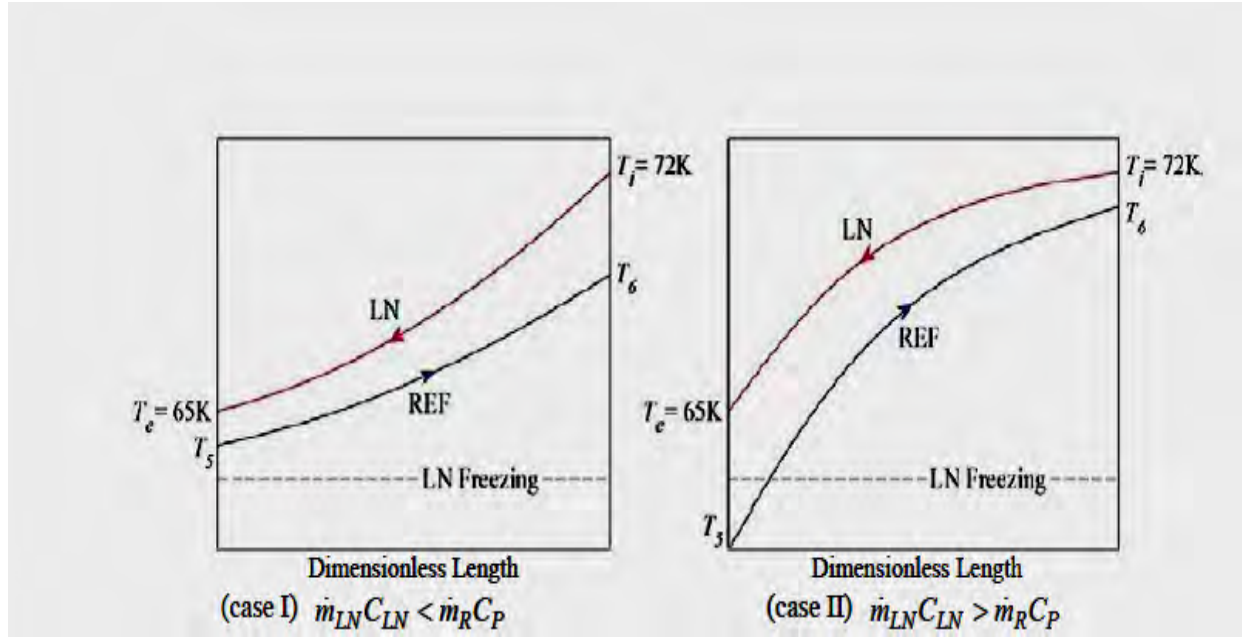


Fig: 4.8 Schematic temperature distribution of liquid nitrogen (LN) and refrigerant (REF) in HX2, depending on the relative magnitude of capacity rate of two streams [34]

4.4.3 Achieving The Maximum Value of FOM (ideal cycle)

As helium and neon have same K value it does not affect the ideal Brayton cycle. A unique model exists for r_p gives the maximum value of FOM. Smaller value of r_p results in higher entropy due to high temperature at the warm end of HX2 (case I) and a larger also gives higher entropy generation because of the high temperature at the cold end of HX2 (case II). As value increases the optimum model of r_p decreases and get near to balanced state (dashed curve). The maximum FOM of ideal (internally reversible) Brayton cycle is 93.6% for this application. The varying of FOM value with pressure ratio is given in figure 4.9.

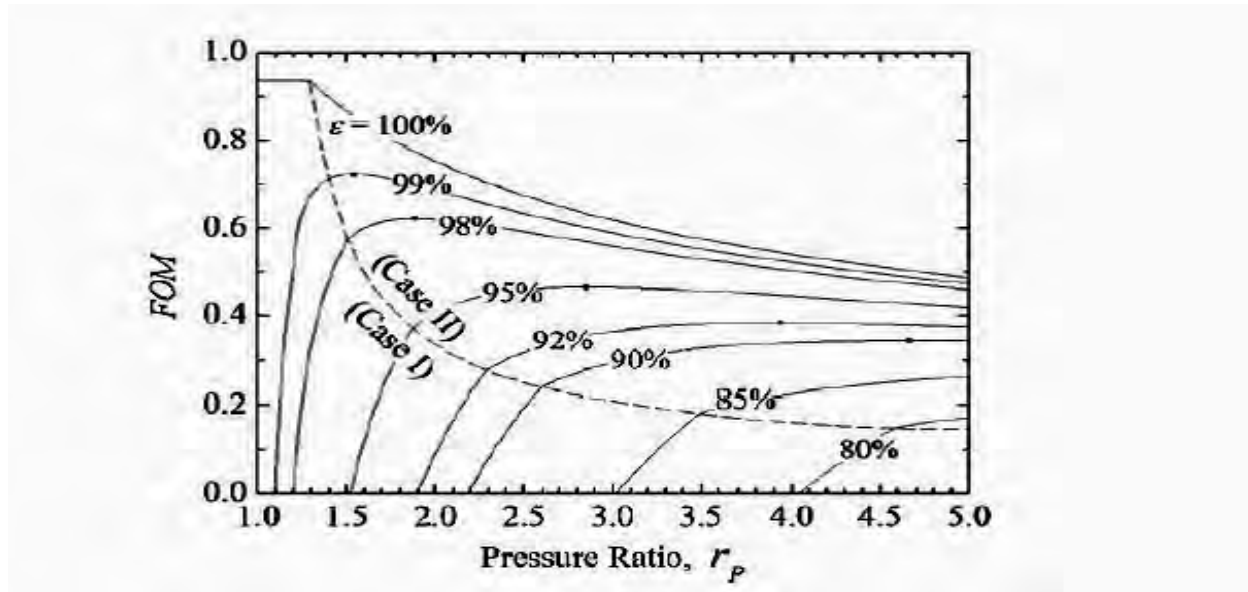


Fig: 4.9 FOM of ideal Brayton cycle as a function of pressure ratio for various values of heat exchanger effectiveness[34]

4.4.4 Practical Cycle Design

In this section the procedure for designing a practical cycle is explained. For a 10 kW practical Braytoncryocooler, design the accompanying assumption are made in this cycle design and analysis:

1. The adiabatic productivity of compressor and expander is 75%.
2. The leave temperature of after-cooler is 300 K.
3. The least temperature difference between the warm and cold streams is 5 K for HX1 and 1.5 K for HX2.
4. The pressure drop in each stream is 50 kPa for HX1 and 20 kPa for HX2 and after cooler.
5. In instance of two-stage compression, the intermediate pressure is resolved to limit the total compressor work.

6. The heat leak from encompassing is irrelevant. It is noted in ③ that HX1 is exceedingly effective (97~98%) for proficient regeneration, yet HX2 is sensibly compelling (82~85%) due to its compactness of LN cooling.

The temperature difference and pressure drop are complicatedly related to each other, so the values in 3 and 4 may be changed iteratively with detailed specification of heat exchangers.. The least temperature point (the pinch point) might be the warm end, the cold end, or amidst heat exchanger, contingent upon the flow rate and working pressure. To incorporate the real properties of helium or neon a set of equation needed to be solved simultaneously containing 12 unknown [34] including the flow rate of refrigerant and the temperature and pressure at 6 points except T_3 (given at 300 K). There are 10 equations, 2 for energy balance of HX1 and HX2, the adiabatic efficiency of the compressor and expander have 2 equations, 2 for temperature difference in HX1 and HX2 and the rest of the four equations is for the pressure drop of each stream in HX1, HX2, and after-cooler. There are two independent variable in cycle design and to compare with ideal cycle, the main variable is taken as the pressure ratio at compressor ($r_p = P_2/P_1$). The second variable is taken as the maximum/highest pressure ($P_H = P_2$). Figure 4.10 below shows the plot of calculated FOM as a function of r_p with various value of P_H [34].

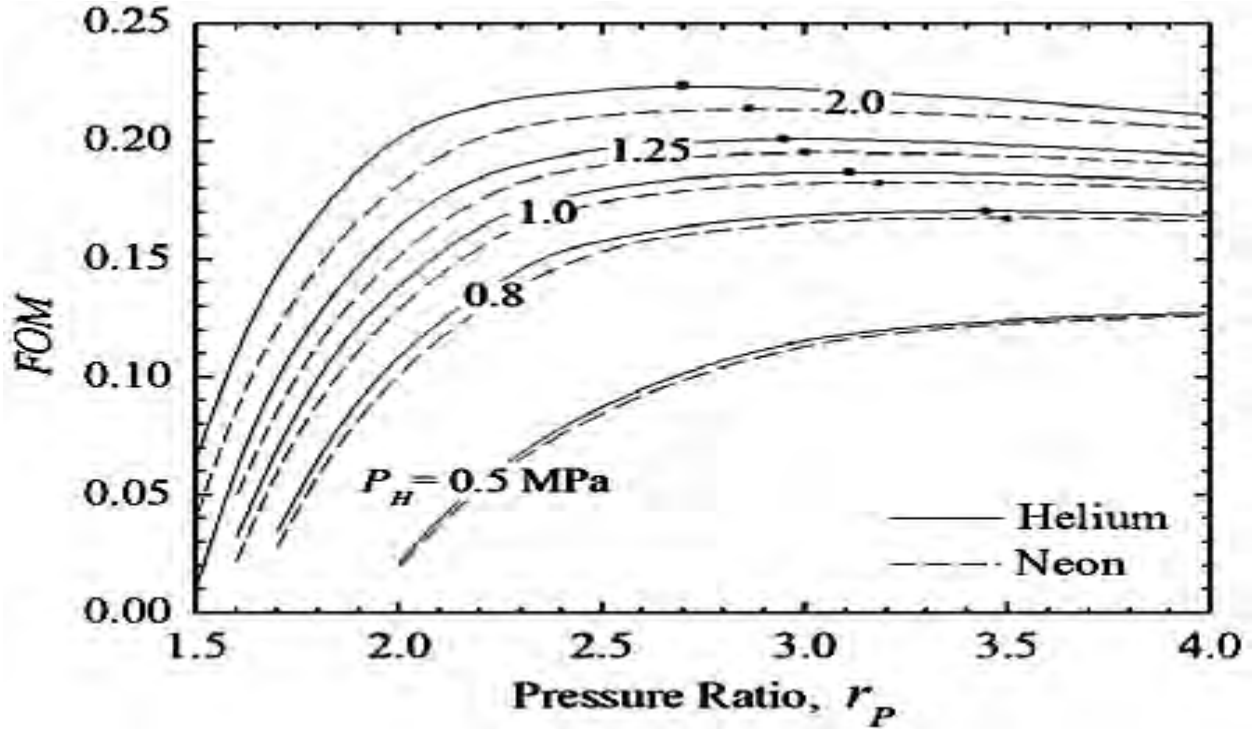


Fig: 4.10 FOM of practical Brayton cycle as a function of pressure ratio for various values of highest pressure with helium and neon as refrigerant[34]

The first problem that is needed to be solved is the selection of refrigerant from helium and neon. In the above figure 4.10 the solid and dashed curves represent the plots for helium and neon, respectively, and the maximum value of FOM points are again indicated by dots. The thermodynamic performance of two gases is nearly same at low P_H , as both gases behave like an ideal gas at low pressure. With increments in P_H helium become more efficient than neon as it can maintain its ideal gas property at higher P_H value because of the genuine gas conduct (particularly, the pressure dependence of enthalpy). Furthermore, helium has a higher thermal conductivity and a smaller viscosity than neon over the temperature run. Taking all these into consideration and to achieve a high FOM (over 20%), helium is chosen as refrigerant, should be around 2~3 and the high pressure should be greater than 1 MPa [34]. The advantage of two-stage pressure is little when r_p is under 2, however its merit become more prominent as r_p value increases over 2. Even though the theoretical value of r_p (indicated by dots) for two-stage compression is as substantial as 3.0~3.5 at $P_H = 1\sim 2$ MPa, the pressure proportion may be determined at 2.0~2.5 with no noteworthy loss in FOM. Because of the heavy flow rate of

refrigerant, two-stage compression with centrifugal compressors is more reasonable under this system/condition. Moreover, the multi-organize compression gives us a way to straightforwardly utilizing the output power from expander to cover one phase of compression with so-called a “compander” [34]. Since the required T_e of liquid nitrogen (65 K) is near its freezing temperature (63.2 K), so the fluid might be solidified close to the exit wall of HX2 if T5 is under 63.2 K. The solid nitrogen would bring about an additional thermal resistance in HX2. As stated earlier, the ideal rP is in the region of case II and T5 may drop well underneath 63.2 K, as exhibited in FIGURE 2. Hence a design constraint is applied so that the wall temperature at the cold end should be greater than 63.2 K [34], thus preventing the solidification of nitrogen.

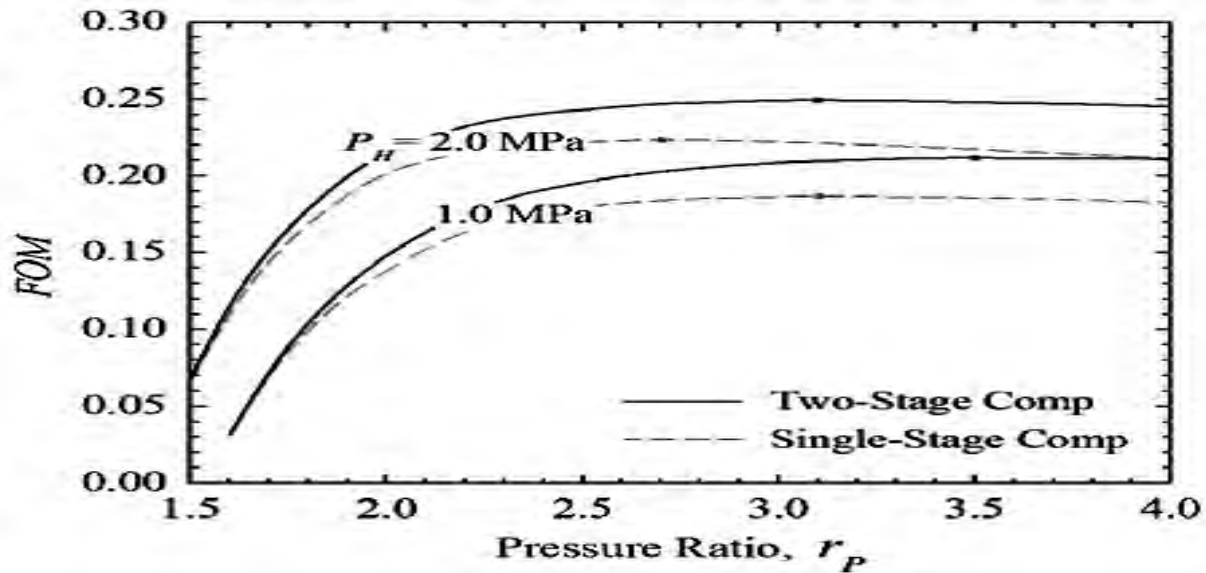


Fig: 4.11 FOM as a function of pressure ratio to compare single-stage and two-stage compressions [34]

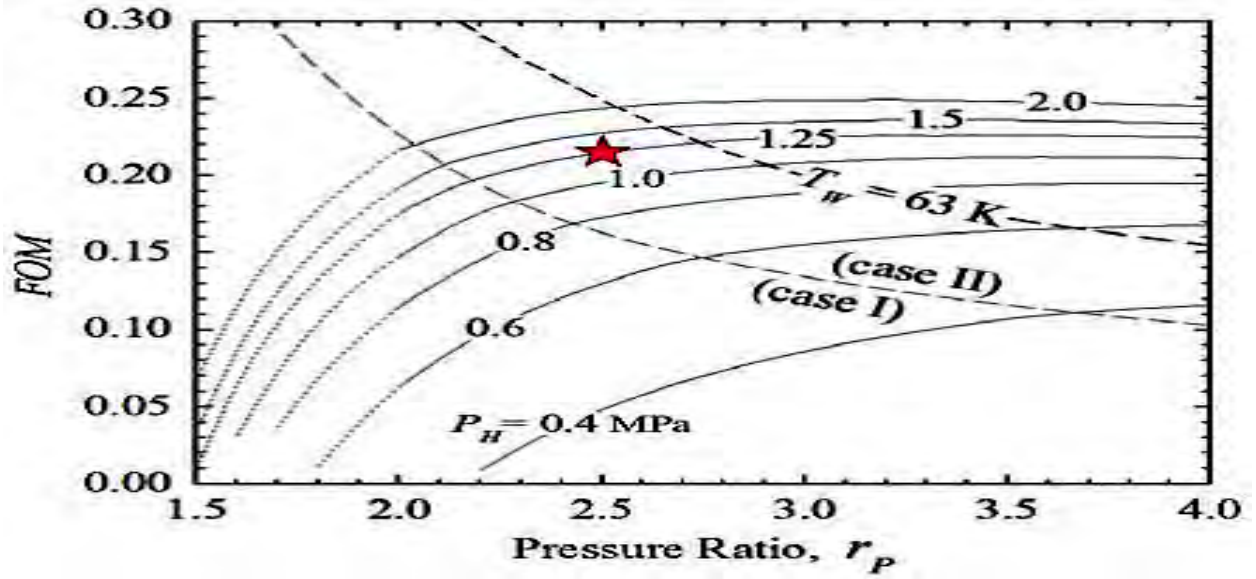


Fig: 4.12. FOM as a function of pressure ratio for various values of high pressure with helium, two-stage compression, and wall-temperature constraint to avoid freezing of liquid nitrogen[34]

The wall temperature T_w , between e and 5 is determined by a model of thermal resistance, neglecting the wall conduction resistance and fouling factors, the equation is given below:

$$h_{LN}(T_e - T_w) = h_R(T_w - T_5)$$

Here h_{LN} and h_R are the convection heat transfer coefficient of liquid nitrogen and refrigerant respectively. The experimental design and study of heat exchanger is beyond the scope of this study but an estimation for the coefficient is made by reviewing the literature [39]. A similar FOM plot for helium is given in figure 4.12 as the refrigerant having two-stage compression, including a curve of $T_w = 63 \text{ K}$. To prevent the liquid nitrogen from freezing in HX2, the operating condition is determined from the left side of the curve [34]. Under this constraint, the operating pressure is finally determined as $rP = 2.5$ and $PH = 1.25 \text{ MPa}$, as indicated by a star in figure 4.12. The complete thermodynamic properties of helium are listed in table 4.1 and the corresponding temperature-entropy diagram is shown in figure 4.13. The net power input is 157.9 kW, and the expected FOM is 21.4%.

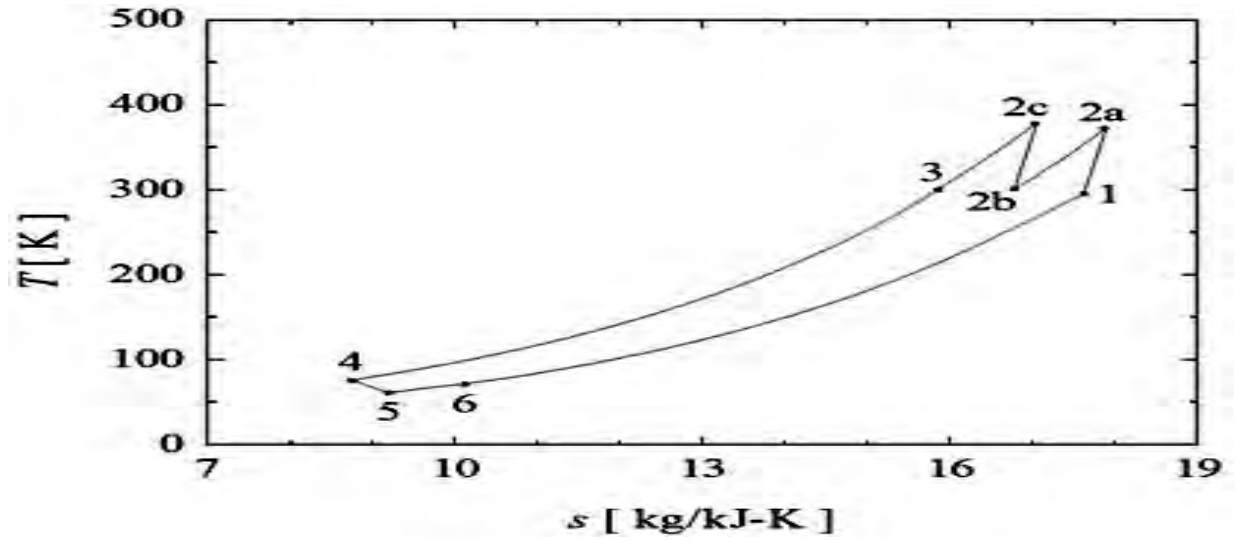


Fig: 4.13 Designed Brayton-cycle cryocooler on temperature-entropy diagram of helium [34]

Helium, 0.2091 kg/s				
	P (MPa)	T (K)	h (J/g)	s (J/g-K)
1	0.506	295.0	-16.86	17.61
2a	0.801	374.0	393.9	17.89
2b	0.791	300.0	9.07	16.77
2c	1.25	380.4	426.9	17.06
3	1.24	300.0	8.78	15.84
4	1.19	75.80	-1159.5	8.750
5	0.576	61.38	-1232.9	9.165
6	0.556	70.50	-1185.1	9.964

Table: 4.1 Thermodynamic properties of helium for designed cycle [34]

4.5 Heat Exchange & Material Properties of Cryocooler

The utilization of intermetallic mixes in regenerators of cryocooler enhanced its working below 10K [32] and liquid He temperatures were came to cryogenic temperature [40, 36].The heat limit of Pb diminishes while in particular heat is seen 10 K [37– 39].

Figure 4.14 speaks to those materials utilized for different temperature ranges regenerators alongside their geometry. These days' cryocooler used to cool magnetometers (SQUIDs) the place as they are high attractive magnetic fields $\sim 5\text{T}$ or a greater amount.

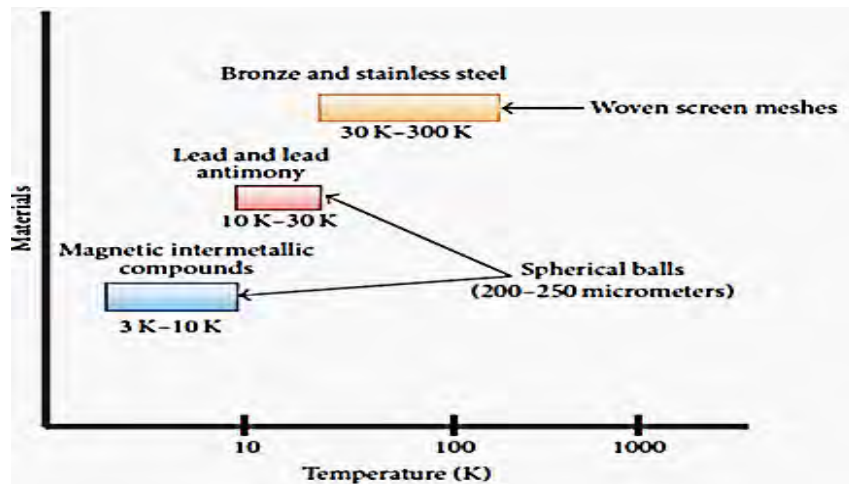


Fig: 4.14 Temperature range for different regenerator materials used in cryocooler[47]

Till date, Different materials have been utilized for 4 k propulsion for cryocoolers. References [37–39] available few of such materials. Spichkin and Tishin [34] also describe such materials alongside their magnetic properties. Similarly as seen from those materials utilized are Er_3Ni , ErNi , HoCu_2 , and ErPr [32].

Those information available magnetic Properties and electrical properties of cryocoolers Regenerator materials are limited. However, regenerator materials are not frequently all the depicted with their magnetic, thermal and electrical properties all the while. These properties would exceedingly nonlinear at cryogenic Temperatures. Therefore, criteria utilized for choosing regenerator material illustrated as follows:

1. Those material show variable heat capacity over temperature ranges beneath 15K under magnetic field. This temperature will measure on scale to the curie temperature (T_{curie}) for paramagnetic materials while it may be set toward Neel. Temperature (T_N) for antiferromagnetic materials. (AFM) [35].
2. T_{curie} or T_N for the material range below 15 K [35].
3. There would be a large number materials accessible to utilize in the regenerator for 4K cryocoolers. However, the materials might be promptly accessible as for every prerequisite. Therefore,. Economically accessible materials to be chose. [35].
4. Er_3Ni is the only material whose relative permeability is highly nonlinear and must be found experimentally always. [35]

Serial No	Material Properties	Value/ Nature
1	Relative permeability	1.3 (assumed linear & constant)
2	Electric resistivity	Temperature dependent
3	Neel temperature (T_N)	7.7 K
4	Density	9290 kg/m ³
5	Thermal conductivity	2W/m K at 50K 0.3W/m K at 5K
6	Specific heat under magnetic field	Temperature & magnetic field dependent

Table: 4.2 Material properties of Er_3Ni for ANSYS[47]

Table 4.2 represents the electrical, thermal, and magnetic properties of Er3Ni that made input to ANSYS. Key points (1)–(4) are justified after observing table 4.2.

4.6 Cryocooler for HTS Aircraft

National Aeronautics and Space Administration (NASA) investigating a conveyed propulsion system known as N3-X. This air craft features a BWB airframe, wing-tip mounted gas. Turbines, Also superconducting ducted fan on the trailing edge [36]. Starting with an electrical perspective, those N3-X researching two types of superconducting material that require different. Cooling states first one is magnesium diboride (MgB_2). Superconductor with a basic temperature (T_c) of 39K [37]. Those. Second will be bismuth strontium calcium copper oxide (BSCCO) for 110 k [38]. The airplane accepts a completely superconducting System for propulsion of energy rating about ~ 80 MW [39]. Predicted generator-to-propulsion loses to those N3-X about 0.03% to those fully superconducting particular idea. Fuel burn for this concept is 72% for the liquid hydrogen (LH_2) cooled MgB_2 version and 70% for the BSCCO version when compared with Boeing 777-200 Long Range (LR) [39].

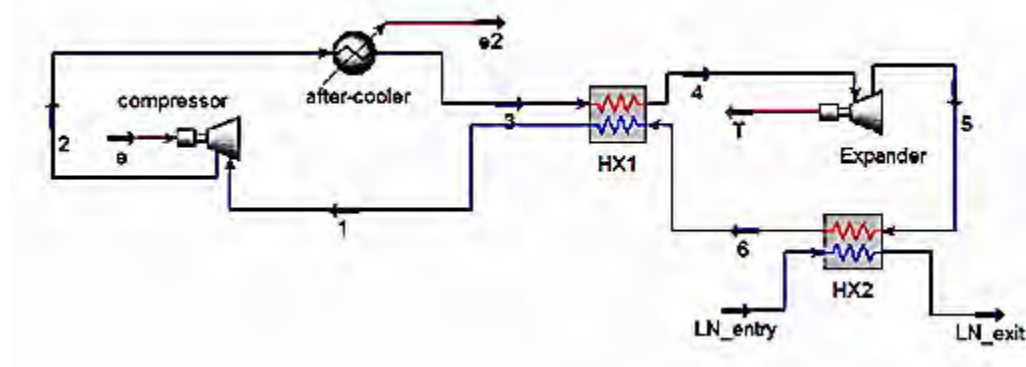


Fig: 4.15 Schematic diagram of Reverse BraytonCryocooler[18]

Utilization of a cryocooler N3-X will be confined of the BSCCO because of those exponential change in cryocooling control. Similarly as temperature cryocooler will trade heat for those encompassing air as the high temperature sink so uproot losses inside those cryostat [41].

4.6.1 Selection of Reverse Brayton cryocooler

Cryogenics is going to be a well-established field in science. However, cryogenics of the particular issue of High-potential superconducting material is new. Machines would even now designed for their outset As far as useful utilization for exactly superconducting machines [42]. Nonetheless there is no referred to outline methodology for fully superconducting machines. Cooling system, in light of it implies that heat losses done any future superconducting system will be not completely calculated For addition, cryogenic cooling likewise require a high potential power itself [41]. While considering the coefficient of performance (COP) for a cryocooler, the low temperatures necessary for superconductivity mean that considerably more power than is absorbed in the cryostat must be put into the system. When fixing the rejection temperature and cold power, the required input power with respect to temperature follows a rough inverse-square curve [43]. This impact of N3-X study shows that possibility of Cryogenic system weight will be between 25 Furthermore 34% of the downright. Propulsion framework weight contingent upon if BSCCO alternately MgB₂ which one Will be utilized [39]. Execution of the superconducting system will shift conversely with the execution of cryogenic framework. The second test is the determination of ideal system that will Convey cryogenic cooling as per require cryogenic temperatures. Possibility future cryocooler advancement much an 80% decrease on weight toward 2035. Recuperative. Cryocooler depend on a consistent flow about unidirectional liquid which take thermal exchange through high temperature Regenerative grid. Cryocooler for example, such that the capacity on bring high rates,. Decreasing warm transient reaction times is reverse-Brayton cycle.

4.7 Result Analysis

4.7.1 Relation of Mass, Power Input Temperature losses & Efficiency

Those reverse-Brayton cycle cryocooler (RBCC) will be viewed as the practically feasible alternative. RBCCs officially being used inside aviation. Requisitions around little control scales, and have exhibited high reliability and efficiency, dependability also efficiency, for some illustrations arriving at 50,000 h. Of maintenance-free operation [44]. RBCC in its basic form consists of a compressor, turbine, and a hot and cold heat exchanger. RBCC the cryocooler is choice for high-power aerospace applications that NASA experiment have also confirmed a two-stage RBCC for their N3-X concept [45]

The data collected from that study shown in the NASA Brayton power systems previously mentioned [47]. The relationship in figure 4.16 shows the curve fit for the cryocooler data, with the relationship shown in (equation 4.9)

$$m_{RBCC} = 27.5 P_{input} e^{-1.225(\log_{10} P_{input})}$$

Where

m_{RBCC} = The weight of the cryocooler

P_{input} = The cryocooler input power in kilowatts.

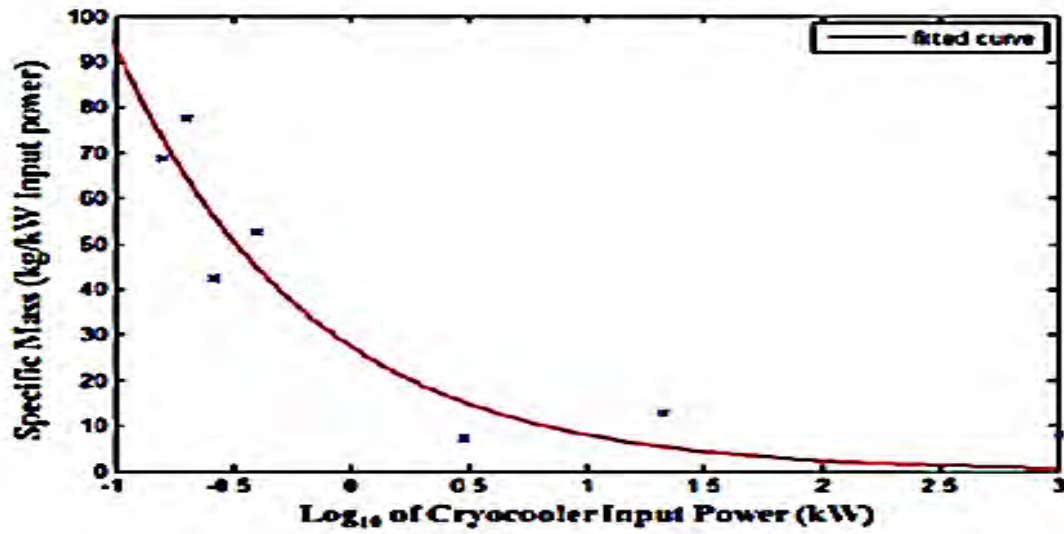


Fig: 4.16 Relationship between specific mass & $\log_{10}$ of input power for known RBCC[18]

RBCC type	Input power, kW	Specific mass, kg/kW
Aerospace	3	7333
Industrial	0.2	77500
Aerospace	0.16	68750
Aerospace	0.26	42308
Aerospace	21	12857
Aerospace	0.4	52500
Industrial	1000	8000

Table: 4.3 List of RBCC cryocooler found with known mass, input power & their respective practical application[18]

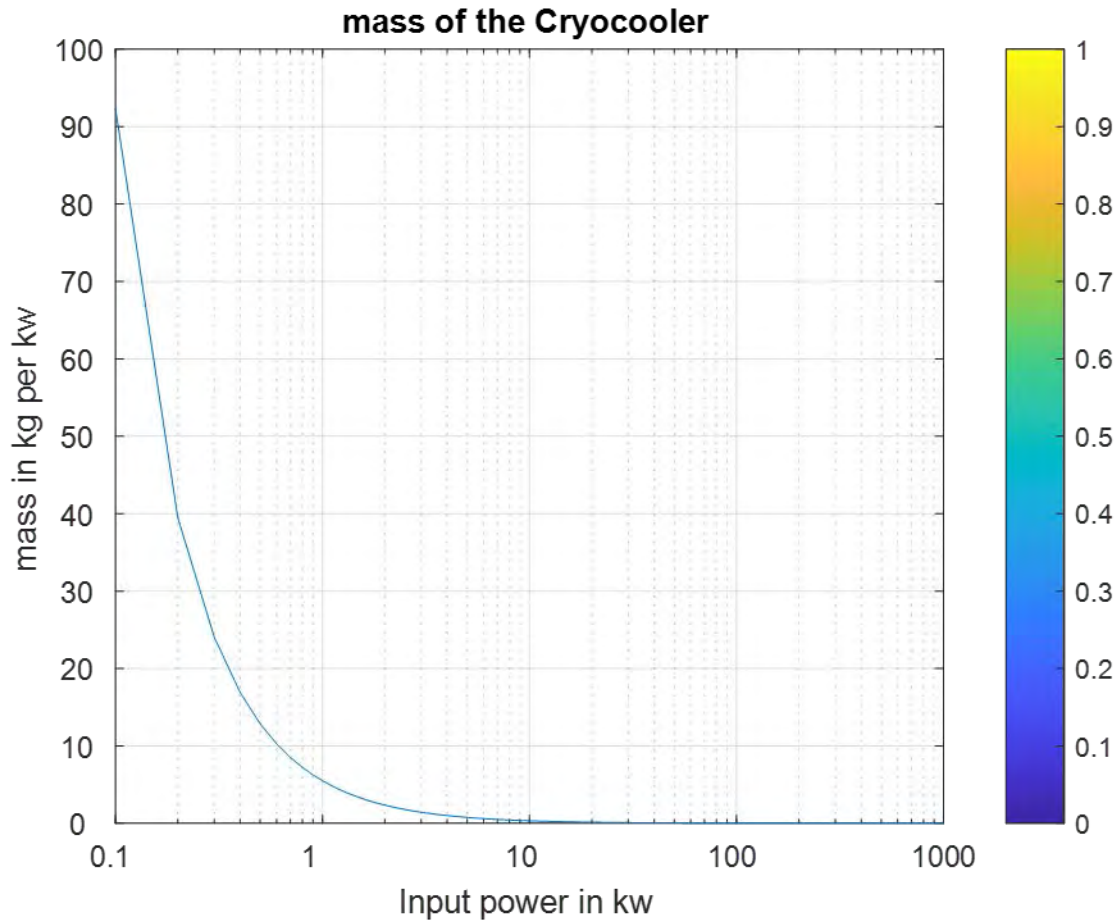


Fig: 4.17 Mass of cryocooler vs Input power

Information indicated that streamlined cryocoolers can be resolve up to 80% at using mechanical materials such-as aviation grade materials [48]. Estimation correctness of $\pm 15.4\%$, with precision possible for 10 kW i power, also diminishing. For low-power illustrations of <1 kW information control future mechanical transformation advancements the applied.Way about this paper for 2035 air craft [38], a questionable matter component from claiming. $<20\%$ is satisfactory [34]. The cryocooler power requirement is calculated with

$$P_{in} = \left(\frac{Q_c}{nf_c}\right) \frac{T_h - T_c}{T_c}$$

Where

$nf_c = 0.3$; the fraction of Carnot efficiency currently thought to be achievable at 3 kg/kW power density [50].

Component	Value	Pess	Med	Opt
Motors/Generator	Efficiency (%)	99.7	99.9	99.97
	Mass (kg)	430	430	430
	Losses (kW)	54	18	5.4
	Delta Fuel Burn (%)	0.6	0.2	0
Cryocoolers	Mass (kg)	918	549	313
	Power Demand (kW)	819	273	81.9
	Delta Fuel Burn (%)	8.8	2.3	0
Power Electronics	Power Density (kW/Kg)	15	30	50
	Mass (Kg)	1200	600	360
	Efficiency (%)	99	99.5	99.9
	Losses (kW)	180	90	1.8
	Delta Fuel Burn (%)	2.6	1	0
Total Delta Fuel Burn		11.5	3.5	0

Table: 4.4a Evaluation of the effect of masses & inefficiency on fuel burn[21]

T_c (K)	T_h (K)	P_{in} (kW)	m_{cyro} (kg)
20	300	840	930
20	111	273	550
60	300	240	520
60	111	51	250

Table: 4.4b Cryocooler power demand & masses [21]

Those cryocooler lessen the fuel burn fundamentally. Utilizing a fluid hydrogen cryocooler will have a chance to be much lighter and more productive. Similarly as a purpose about comparison, airplane designed over 9% emission if lift-to-drag ratio of 21% compared to general aircraft [41]. Table 4.4b compares the cryocooler power demand and mass for different operating and heat sink temperatures. When operating and using a cryocooler at 20 K for MgB₂, a heat sink such as LNG will be required, which can also be used as a fuel operating at 60 K by using YBCO or BSCCO

a) $T_H = 225 \text{ K}$ (air at 32,000 ft.)						b) $T_H = 111 \text{ K}$ (LCH ₄ boiling point)					
η_{fc}	0.1	0.2	0.3	0.4	0.5	η_{fc}	0.1	0.2	0.3	0.4	0.5
$T_c \text{ (K)}$	Power demand (kW)					$T_c \text{ (K)}$	Power demand (kW)				
60	5.5%	2.8%	1.8%	1.4%	1.1%	60	1.7%	0.9%	0.6%	0.4%	0.3%
50	7.0%	3.5%	2.3%	1.8%	1.4%	50	2.4%	1.2%	0.8%	0.6%	0.5%
40	9.3%	4.6%	3.1%	2.3%	1.9%	40	3.6%	1.8%	1.2%	0.9%	0.7%
30	13.0%	6.5%	4.3%	3.3%	2.6%	30	5.4%	2.7%	1.8%	1.4%	1.1%
20	20.5%	10.3%	6.8%	5.1%	4.1%	20	9.1%	4.6%	3.0%	2.3%	1.8%
15	28.0%	14.0%	9.3%	7.0%	5.6%	15	12.8%	6.4%	4.3%	3.2%	2.6%

Table: 4.5 Power demand at different temperature with efficiency

4.7.2 Brayton Cycle Efficiency

The efficiency of the cycle is given by the benefit over the cost or

$$\eta = \frac{W_{net}}{Q_H} = 1 - \frac{Q_L}{Q_H} = 1 - \frac{mc_p(T_4 - T_1)}{me_p(T_3 - T_2)} = 1 - \frac{T_1 \left(\frac{T_4}{T_1} - 1\right)}{T_2 \left(\frac{T_3}{T_2} - 1\right)}$$

If we use the isentropic equations with the ideal gas law, we see that

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} = \left(\frac{P_3}{P_4}\right)^{\frac{k-1}{k}} = \frac{T_3}{T_4} \Rightarrow \frac{T_4}{T_1} = \frac{T_3}{T_2}$$

And

$$\eta = 1 - \frac{T_1}{T_2} = 1 - \frac{T_4}{T_3}$$

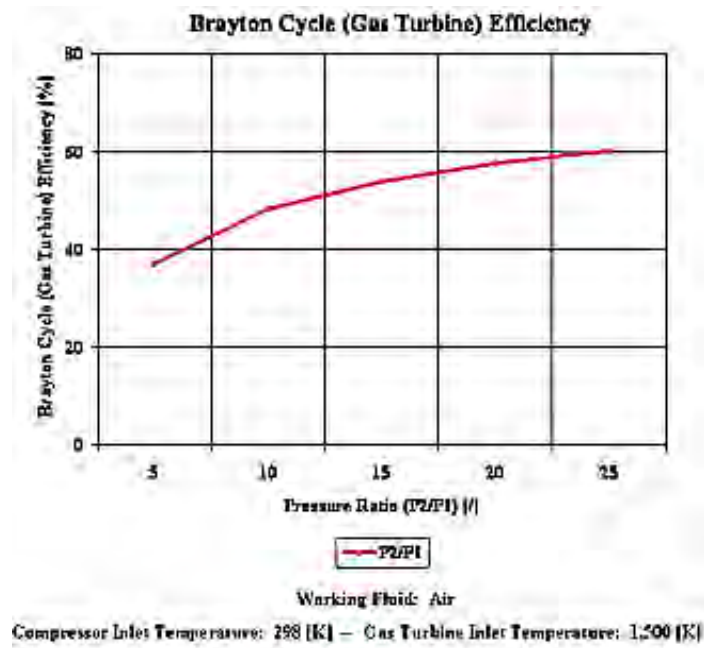


Fig: 4.19 Single stage Brayton cycle efficiency

$$n = 1 - \frac{T_1}{T_2} = 1 - (P_1/P_2)^{(\gamma-1)/\gamma}$$

Temperture on hot side	75°C
Temperture on cold side	25°C
Load resistance	10Ω

Table: 4.6 Boundary conditions[18]

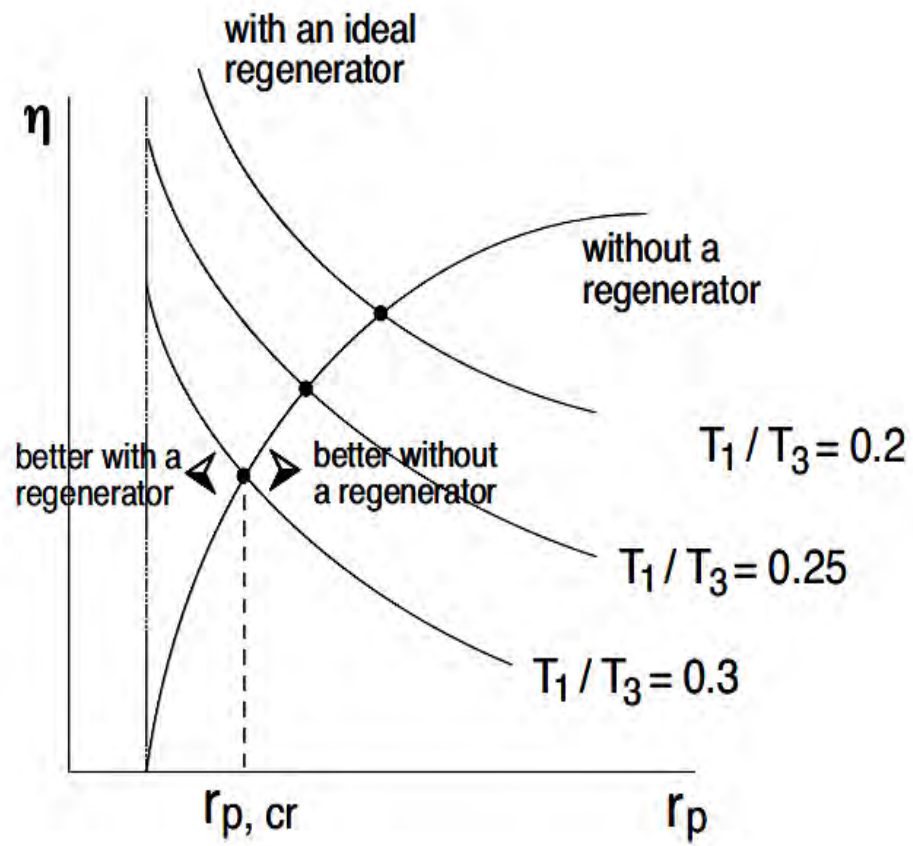


Fig: 4.20 Difference of temperature ration with and without regenerator [18]

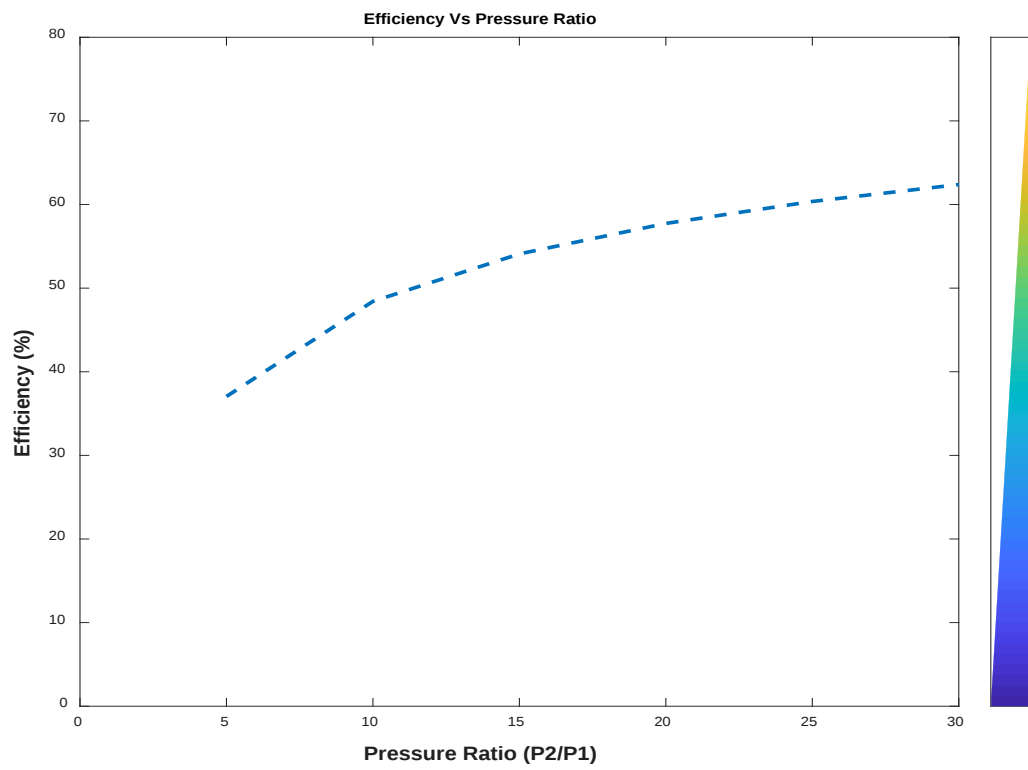


Fig: 4.21 Simulation data of efficiency vs pressure.

4.7.3

Future Framework of 2 stage RBCC

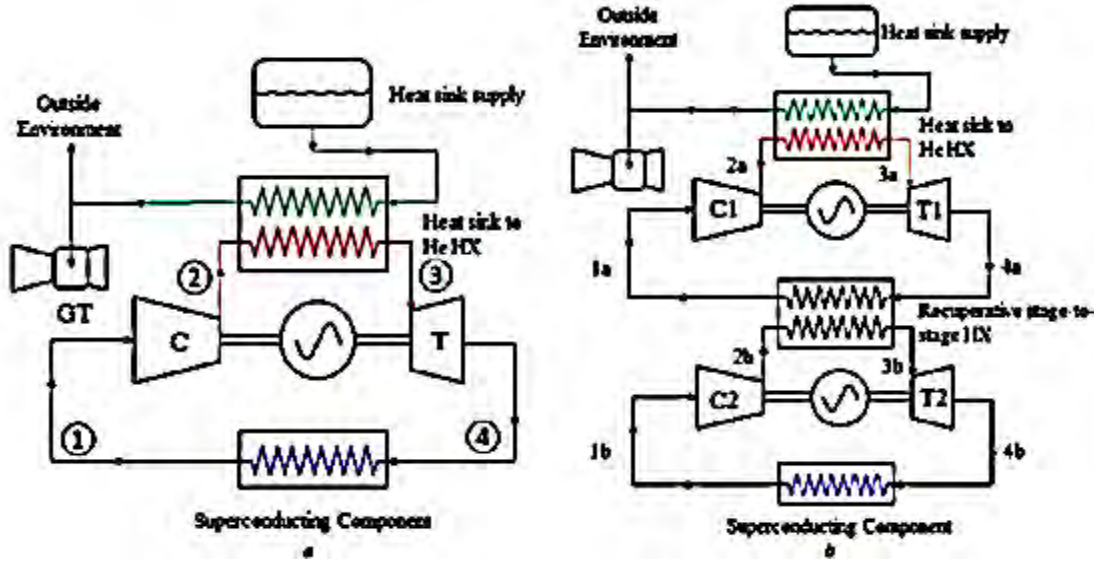


Fig: 4.22 Schematic overview for the single-stage model[18]

Figure 4.24 shows the schematic overview for the single-stage model, developed using the relationships outlined by Swift [46]. Initially a mass flow rate $\dot{m}$ is calculated using the superconducting cold loads of the network and cryocooler motor, Q_{cold} and Q_m , respectively

$$\dot{m} = \frac{Q_{cold} + Q_m}{C_p \Delta T_{4-1}}$$

Since pressure is known, the turbine pressure ratio can be determined as T_3 and is defined as the heat sink input temperature

$$P_3 = P_4 \left(\frac{T_3}{T_4} \right)^{\left(\frac{1}{\eta_{pet}} \frac{\gamma}{\gamma-1} \right)}$$

Turbine energy recovery parameter

$$Q_t = mC_p \Delta T_{3-4}$$

The turbine inlet pressure P_3 to determine the compressor outlet pressure P_2

$$P_3 = \frac{P_2}{1 - \Delta P_{Hxw}}$$

Since the compressor pressure ratio is now known, the compressor temperature ratio can be calculated using the compressor polytropic efficiency, η_{pcc} :

$$T_2 = T_1 \left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma \eta_{pcc}}}$$

The required compressor input energy Q_c can be calculated since mass flow is conserved and all other information are known

$$Q_c = mC_p \Delta T_{2-1}$$

The efficiency is calculated as below

$$\eta_{RBC} = \frac{Q_{cold} + Q_m}{Q_{input}}$$

$$n = 1 - \frac{T_1}{T_2} = 1 - (P_1/P_2)^{(\gamma-1)/\gamma}$$

Two-stage. RBCC's would regularly utilized when those temperature differential. Between the high temperature sink Furthermore cooled part will be higher. Displaying. Two-stage frameworks is to a degree a greater amount intricate over with Single-stage RBCC.. The method developed during this paper creates an equal turbine temperature ratio share. Equation (4.20) shows the method

$$\frac{T_{3b}}{T_{4b}} = \sqrt{\frac{T_{3a}}{T_{4a}}}$$

Here, a represents the warm stage and b represents the cold stage. Since the turbine inlet for the cold stage, T_{3b} is unknown, the turbine outlet temperature for the cold stage T_{4b} (defined by the desired cold temperature) can be used alongside the warm stage turbine inlet temperature T_{3a} in order to give an overall system turbine temperature ratio. The square root gives the turbine temperature ratio that ensures each stage is running at the optimum equal COP. To prevent either the hot or cold stages from efficiency restriction when considering the Carnot efficiency, the COP for each stage must also be equal [41].

4.7.4 Superconductor & Heat Sink Temperature Boundary Condition

Those simulations done for the greater part different variables heat exchanger. Temperature differential would affixed. Table 4.6 depicts the model information parameter presumptions utilized for this paper.

Model input parameters	Parametric model assumptions
cold heat exchanger ΔT , K	10; any higher-end performance of the superconductor is negatively impacted
heat sink heat exchanger ΔT , K	from compressor outlet temperature (T_2) down to heat sink inlet temperature (latent heat capacity considered)
helium specific heat, C_p , kJ/kg K	5.2; assumed constant over the range of temperatures in this paper
helium ratio of specific heats	1.66; constant over the temperature range
compressor polytropic efficiency, %	75% (pessimistic; based on present day technology) 85% (realistic; based on best industrial compressors) 90% (optimistic; based on best aerospace compressors)
turbine polytropic efficiency, %	2% better than corresponding compressor in all cases
ambient helium pressure, Bar	2; this was selected as an arbitrary value for pressure ratio derivation
superconductor temperature, K	20 K for MgB_2 concepts 65 K for BSCCO concepts
heat exchanger pressure drop, %	5% (optimistic, based on low transport and turbulence loss) 10% (realistic, based on medium transport loss and turbulence) 15% (pessimistic, based on high transport loss and turbulence)

Fig: 4.23 Model development data for 2nd stage RBCC [18]

Fig 4a (figure 4.25) shows a single-stage RBCC utilizing air and high temperature sink which is generally needed. Effectiveness between 0.39 and 0.82%, Restrictive for MgB_2

superconductors. LCH4 high temperature sink demonstrating a effectiveness of the middle of 1.9 - 4. 1%. LH2 idea is more modest for single-stage RBCC that Might be utilized in cooling components. Temperature to 10 k starting with the 20 k LH2 coolant, Carnot efficiency, and general efficiencies indicated between 17 - 53%. Fig. 4b (figure 4.25) indicates the association between those superconductor mass and temperature. In fact, sensitivity of input power and high temperature sink temperature is reflected. Fig. 4c (figure 4.25) indicates the variety of mass of the cryocooler particularly for Superconducting temperature. Demonstrated on the chart nasa target to achieve 3 kg/kW.

On account of the N3-X concept, those model presumptions contrast superconducting part temperature is 65 k and the load is expanded from 10 will 12 kw. Those. Increment for load reflects those 24 kW. Generally two stage rbcc is required. Fig. 4d (figure 4.25) shows the relationship between heat sink temperature and the predicted required specific mass of the concept cryocooler. The cryocooler concept is a two-stage design similar to that outlined in the N3-X study.

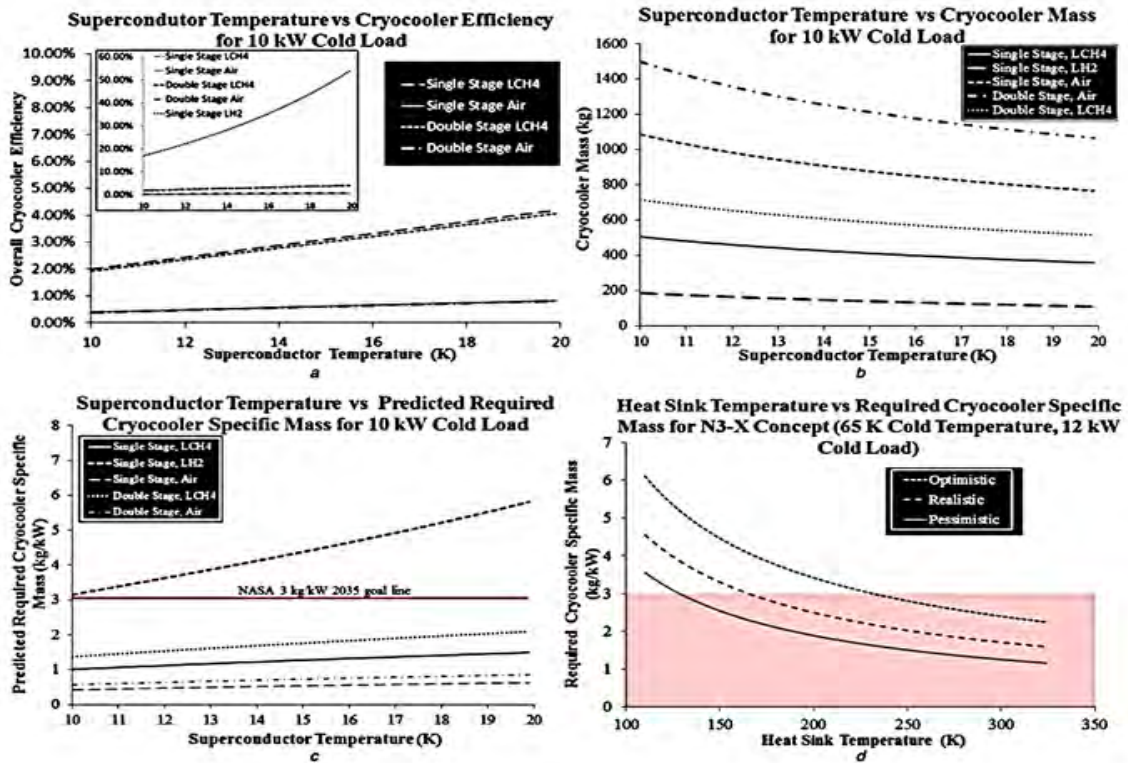


Fig: 4.24 Superconducting temperature vs Mass for 2nd stage RBCC [18]

Fig. 5a (figure 4.26) demonstrates how those single-stage varies When changing the weight drop in each heat exchanger along with compressor and turbine polytropic effectiveness. Those turbine. Polytropic effectiveness is accepted up to 2%. The chart indicates that those extent of. Qualities for the single stage doesn't meet NASA's 3 kg/kW goal. Fig. 5b (figure 4.26) demonstrating efficiency of those two-stage concept that proposed for aircraft with specific mass. Whilst in. Fig. 5a starting with the minimum effective would be 1. 3 kg/kW, those two-stage exhibits additions of 1.8 kg/kW. This data give clear Decision that two-stage ideas are more viable, both to numerical terms and development for provided parameters.

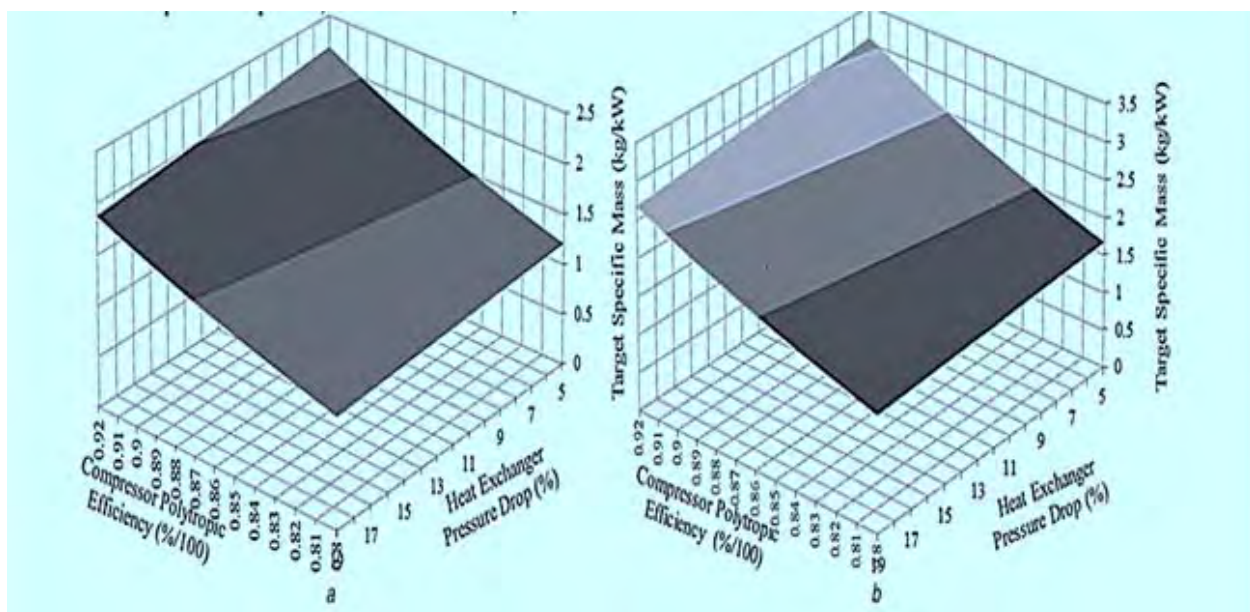


Fig: 4.25Ansys graph at different temperature and mass[18]

4.7.5 Design in ANSYS

The subsections describe the Different steps for modeling the regenerator for ideal measurements, loads and. working conditions.

Solid model:Those regenerator viewed as may be 100mm length and 20mm wide totally. A 2D axisymmetric model for non-uniform attractive field is considered. Those non-uniform magnetic field may be recreated by executing or neglecting Solenoid/coil in the region of the regenerator. Figure 3 indicates solid model used for simulation.

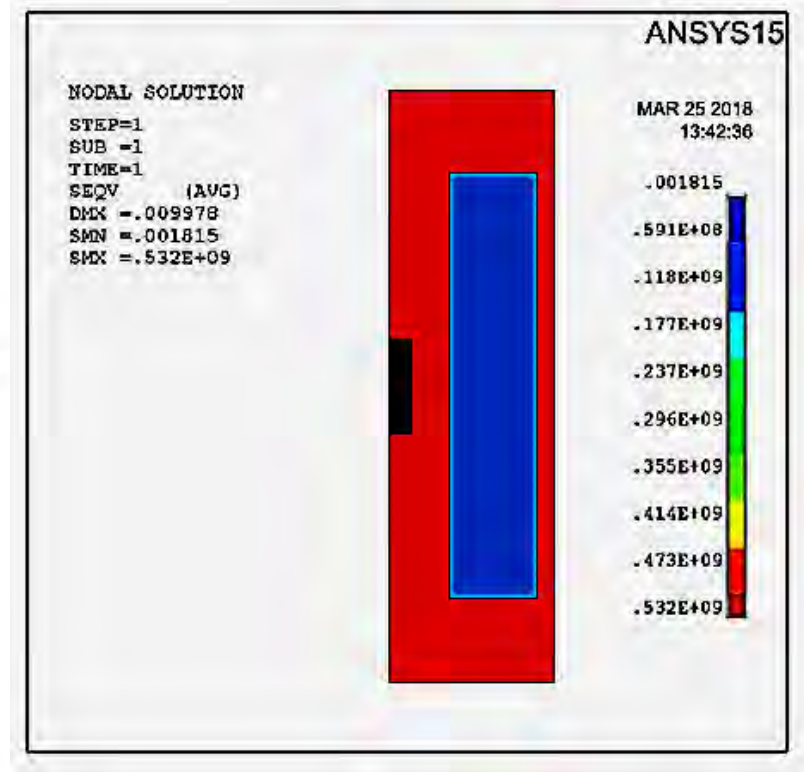
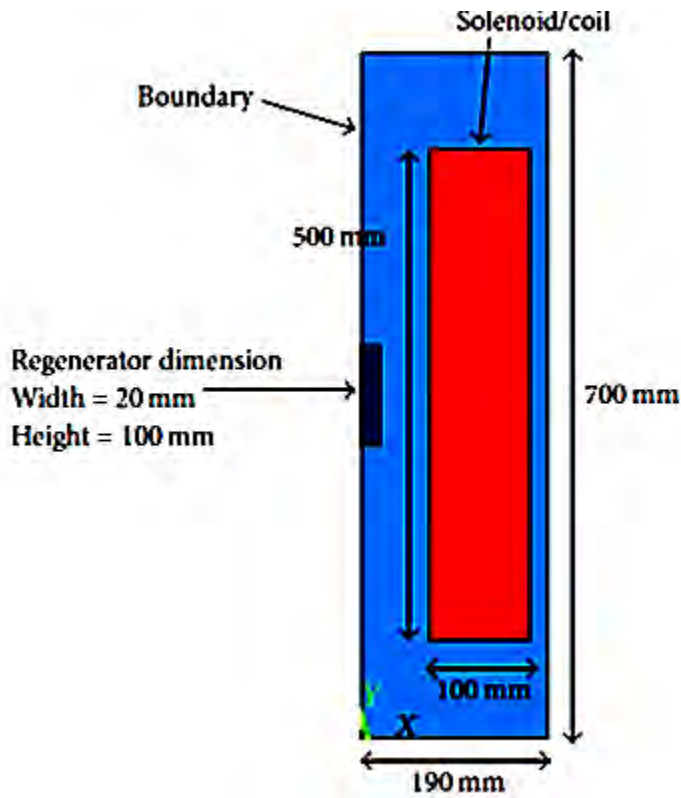


Fig: 4.26 Solid Model in ANSYS

Element Selection: Plane13 (vector quad 13) element is selected for the analysis [46]. 2D thermal, magnetic, and electrical field calculations with limited coupling between the fields can be generated. Plane13 is defined by four nodes with up to four degrees of freedom per node. The element has the nonlinear magnetic capability for modelling B-H curves of the material considered. It can be meshed in quadrilateral as well in triangular forms [35].

Meshing: The results are highly dependent upon the mesh sizes used for the solution. Since the regenerator area is of interest, fine meshing can be seen at it (Figure 4.28). It leads to faster convergence rate and relatively less computational time. The validation of mesh size is done by

continuously refining the initial guess until there is no appreciable change in the results. At last a mesh size of 0.0005 was found to be optimal [35].

Loads. The magnetic loads and thermal loads are explained by Kumar and Shoor [47] in detail along with the magnetic analysis and boundary conditions. Table 4.7 shows the operating conditions used for simulation.

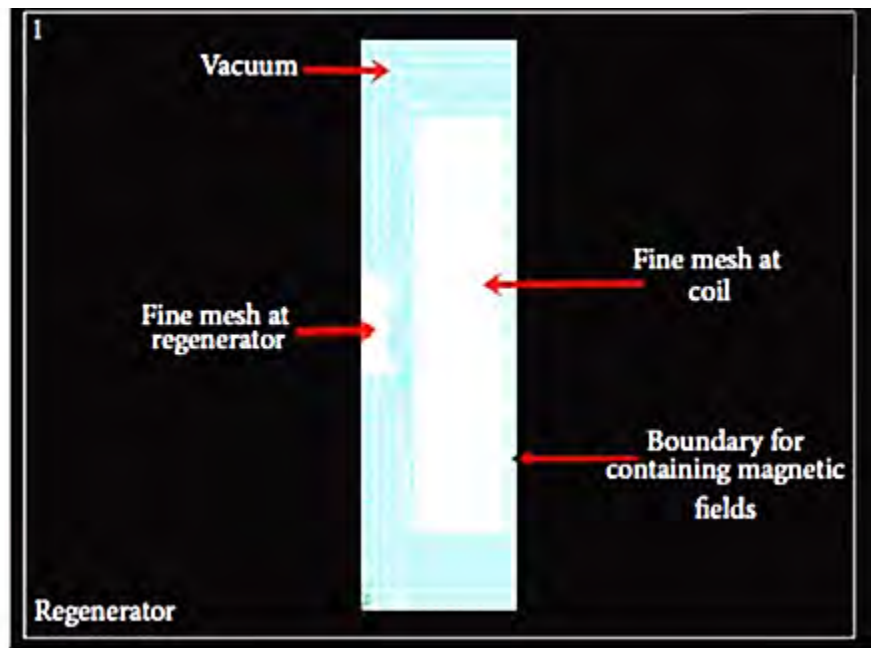


Fig: 4.26 Meshing of solid model in ANSYS[47]

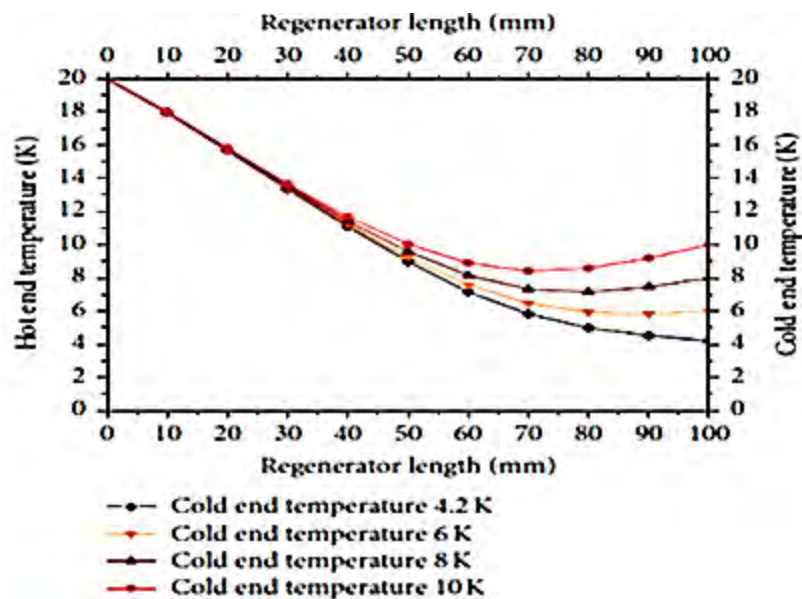


Fig: 4.27 Temperature profile of model at B=0T[47]



Fig: 4.28 Temperature and pressure data of ansys

Results of ANSYS Fluent Release 16 (ANSYS, Inc. 2017) simulation of the mine-scale eductor. Mass flow of compressed air = 22.36 kg/s, static pressure rise across the eductor = 1 kPa, inlet mine (auto-compressed) air temperature 39°C, air temperature and velocity at nozzle exit = -71.4°C, 354.9 m/s.

	$B = 0\text{ T}$	$B = 1\text{ T}$	$B = 3\text{ T}$	$B = 4.3\text{ T}$
Hot end temperature $T_H = 20\text{ K}$	$T_C = 4.2\text{ K}$	$T_C = 4.2\text{ K}$	$T_C = 4.2\text{ K}$	$T_C = 4.2\text{ K}$
	$T_C = 6\text{ K}$	$T_C = 6\text{ K}$	$T_C = 6\text{ K}$	$T_C = 6\text{ K}$
	$T_C = 8\text{ K}$	$T_C = 8\text{ K}$	$T_C = 8\text{ K}$	$T_C = 8\text{ K}$
	$T_C = 10\text{ K}$	$T_C = 10\text{ K}$	$T_C = 10\text{ K}$	$T_C = 10\text{ K}$

Table: 4.7 Temperature difference at different Magnetic Flux of the hts motor [47]

4.8 Summary

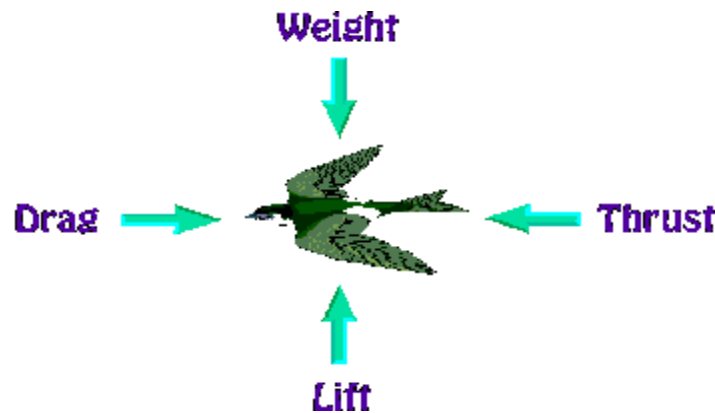
In this section the overall simulated study on the cryocooler was done by changing the coolant and the working procedure, modelling of different cryocooler was thoroughly studied. As for further studies/ future works, by 2035 NASA proposed to design the cryocooler with 2nd stage for the future aircraft. RBCC cryocooler is more efficient than other cooling system. It has many possibilities to developed different parameters along with the development of the HTS cable. A coolant liquid nitrogen from 72K to 65K is needed for this proposed aircraft. A perfect Brayton cycle for this application better considering the performance of expander, and heat exchangers.

Chapter 5

Ansysis Simulation, Analysis & Comparison with MATLAB Results

5.1 Aurora D8 Simulation & ComparisonWith MATLAB Results

According to aerodynamic design, the lift co-efficient, angle of attack and stability velocity can be different. As we are our using Aurora D8 aircraft [1] as our thesis, there are some differences in the parameters like span, wing length, weight due to cryocooler and hts motor, position of the engine and also the fuselage area.



Any flight is made possible by a careful balance of four physical forces: lift, drag, weight, and thrust. For flight, an aircraft's lift must balance its weight, and its thrust must exceed its drag. A plane uses its wings for lift and its engines for thrust. Drag is reduced by a plane's smooth shape and its weight is controlled by the materials it is constructed of. It needs to be more lift

force than the weight of the aircraft to lift and to land, the drag must be more than the thrust force. There are different parts to control these for forces and these are minimum true velocity of lift, lift coefficient and minimum flying speed.

Minimum True Velocity for lift: The aircraft generates lift by moving quickly through the air. The wings of the vehicle have aero foil shaped cross-sections. For a given flow speed with the aero foil set at an angle of attack to the oncoming airstream, a pressure difference between upper and lower wing surfaces will be created. There will be a high pressure region underneath and a very low pressure region on top. The difference in these pressure forces creates lift on the wing. The lift produced will be proportional to the size of the aircraft; the square of its velocity; the density of the surrounding air and the angle of attack of the wing to on-coming flow. To simplify the problem, lift is typically measured as a non-dimensional coefficient and the relation which relates this is given in equation 5.1.

$$L = W = CL \frac{V^2 S \rho}{2}$$

$$or, V = \sqrt{\frac{2W}{S \rho CL}}$$

$$or, V = \sqrt{\frac{2mg}{S \rho CL}}$$

Here,

CL= Lift Co-efficient;

V= True Velocity from the Ground;

ρ = air density;

L= lift;

W= weight=mg;

S= span;

For Aurora D8 we get the following parameters from literature [1],

$L=W=228510.2162\text{ N}$;

$\rho = 1.2250\text{ Kg/m}^3$ [for 0m height from the ground];

$S = 170\text{ fts} = 51.816\text{ m}$;

The value of ground velocity obtained for different lift coefficient is tabulated in table 5.1

Air density P (row) kg/m^3	Span meters	Weight mg	Lift Co-efficient CL	True Velocity V kmph
1.2250	51.816	228510.2162	1.75	230.92
1.2250	51.816	228510.2162	1.90	221.61
1.2250	51.816	228510.2162	2.10	210.80
1.2250	51.816	228510.2162	2.20	205.95

Table: 5.1 Result of ground velocity for different lift coefficient

Lift Co-efficient is related to angle of attack by which the lift occurs and aircraft fly [49]. This angle of attack depends on the foil body of the aircraft and is around 0-15 degree according to the length of the runway of airport. If the airport runway length is more the angle of attack is less and the true velocity of the aircraft will be low which means the efficiency is higher. For our model, as the foil body is more than the other aircraft like Boeing-747, the air pressure that our aircraft can take more which also helps to make more efficient in power consumption. As lift co-efficient need to fix experimentally, we have assume some different values by comparing lift of aircraft having similar shape likeboeing-747 which is 1.8.A nearest values of it due to having thin and large wing, the fuselage, the total surface area of the aerodynamic design of aurora D8.

As the lift co-efficient is inversely proportional to square of the velocity according to equation 5.1, so a smaller value of lift coefficient means a higher velocity. However, it also means more power is consumed to lift the aircraft. So in other words the higher lift-coefficient, the lower velocity and it can be achieved to a particular value due to the angle of attack. This relation is simulated in MATLAB by inserting the variables and the results is given in fig 5.1. According to the result the minimum value is 156.

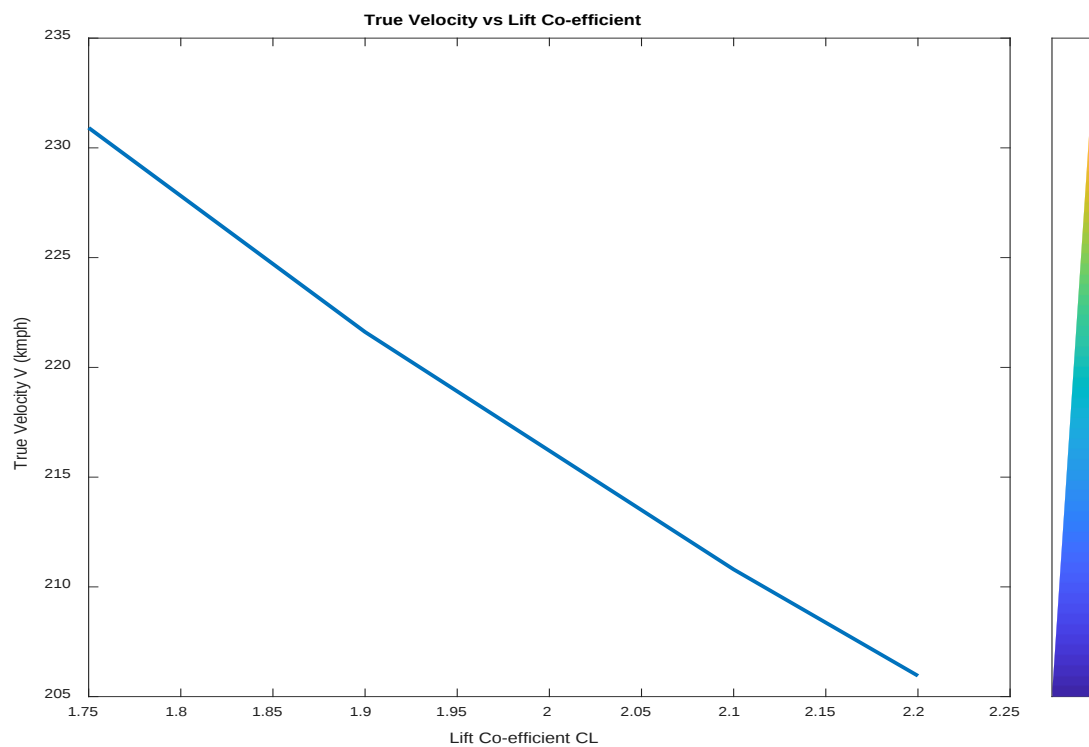


Fig: 5.1 Minimum True Velocity vs Lift coefficient

Lift Co-efficient: Lift co-efficient is a lift constant which has a large effect on lifting and take off. There are four forces work to the aircraft. Lift, to the upward, weight to the downward, thrust for the forward and drag is for the backward. Thrust and lift force act together in order to lift the aircraft body [3] and for stable scenario lift and weight is equal. In order for the aircraft to experience lift it is must be more than the weight. According to the equation 5.2, the lift is

proportional to its lift co-efficient. Lift co-efficient CL which is needed to be determined experimentally.

The angle for which the aircraft lifts is called angle of attack and this is directly proportional to lift coefficient. The more the lift co-efficient, the more the angle of attack. The runway also important for the angle of attack. If the angle of attack is less, the aircraft must take lots of time to lift and for this, it needs a long runway. On the other hand, it needs less velocity for lifting. To find out the lift co-efficient [3], the equation that we need to analyze is given below (equation 5.2)

$$CL = CL\alpha * \alpha + CLo$$

Here,

$CL\alpha$ =Lift co-efficient for Alpha Value

CLo =Actual Lift Co-efficient;

CL = Lift Co-efficient;

α = angle of Attack;

$$CLo = \frac{2\pi}{1 + \frac{2}{AR}}$$

Here,

AR = *Aspect Ratio*, which is

$$AR = \frac{Span^2}{Wing Area}$$

Lift Coefficient due to lift,

$$CL\alpha = \frac{\partial CL}{\partial \alpha}$$

As the curve of Lift co-efficient vs. angle of attack is not linear which is found out from the simulation results, so the slope is not same all the points. For different angles, we get the

different slope which can be seen in fig 5.2. From the reference paper, we have got some different $CL\alpha$ for different angle.

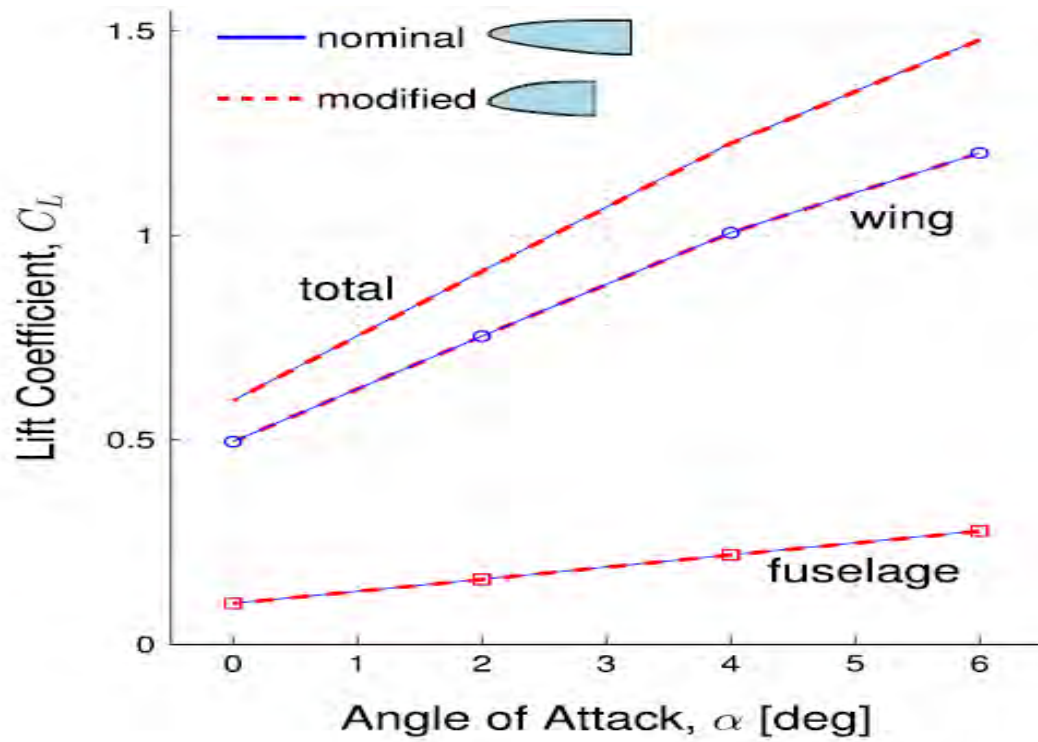


Fig: 5.2 Lift co-efficient Vs Angle of attack [1]

From the above graph [1], we get the value of $CL_0=0.54$, 0.836, 1.133 and 1.379 for angle of attack 0, 2, 4 and 6. The respective simulated results are tabulated in table 5.2.

Angle of Attack α (degree)	Zero Lift Co-efficient, CL_0	Lift due to angle of attack, $CL\alpha$	Lift Co-efficient CL	Lift Co-efficient (Simulation), CL_1	Error (in %)
0	0.54	8.5	0.540	0.619	12.76
2	0.54	8.5	0.836	0.749	11.62
4	0.54	8.5	1.133	1.226	9.22
6	0.54	8.02	1.379	1.461	5.61

Table: 5.2 Simulated and theoretical value of lift coefficient with different angle of attack

The simulation is carried in ANSYS and the graphical results are given in fig 5.3 and it can be seen that the percentage difference between our results and the experimented value is within 20% the lift co-efficient are close to the theoretical values.

Minimum Flying Speed: From the typical lift coefficient graph, it can be seen that there exists a maximum lift coefficient (CL_{max}) for the aircraft. This sets the absolute lower speed limit for flight. If the aircraft attempts level flight below this minimum speed then, for Lift to equal Weight, with other parameters (such as density and area) fixed, then the aircraft would require an attitude that produced a lift coefficient larger than the maximum possible.

Using angles of attack that exceed the maximum lift coefficient causes the wing flow to separate and the aircraft to stall. So, the minimum speed where the aircraft is at maximum attitude and maximum lift coefficient is called the stall speed [3]. By applying the equilibrium equation at this speed, the stall conditions can be calculated. So stall speed (V_s) will be

$$V_s = \sqrt{\frac{mg}{\rho S C L_{max}}}$$

Here,

ρ = Air density;

CL_{max} = Maximum Lift Co-efficient;

S = Span length;

Due to different height from the sea level, the air density is different. That's why we have the different velocity to stable the aircraft in the sky. The data in table 5.3 are simulated in MATLAB and fig 5.3 shows the range of minimum velocity with different air densities.

Maximum Lift Co-efficient, C_{Lmax}	Span (m)	Height fts	Air density P(row)	Steady speed Velocity kmph
2.20	51.816	3000	1.12102	152.23
2.20	51.816	10,000	0.904637	169.46
2.20	51.816	15,000	0.770816	183.58
2.20	51.816	30,000	0.458312	238.08

Table: 5.3 Minimum velocity at different densities

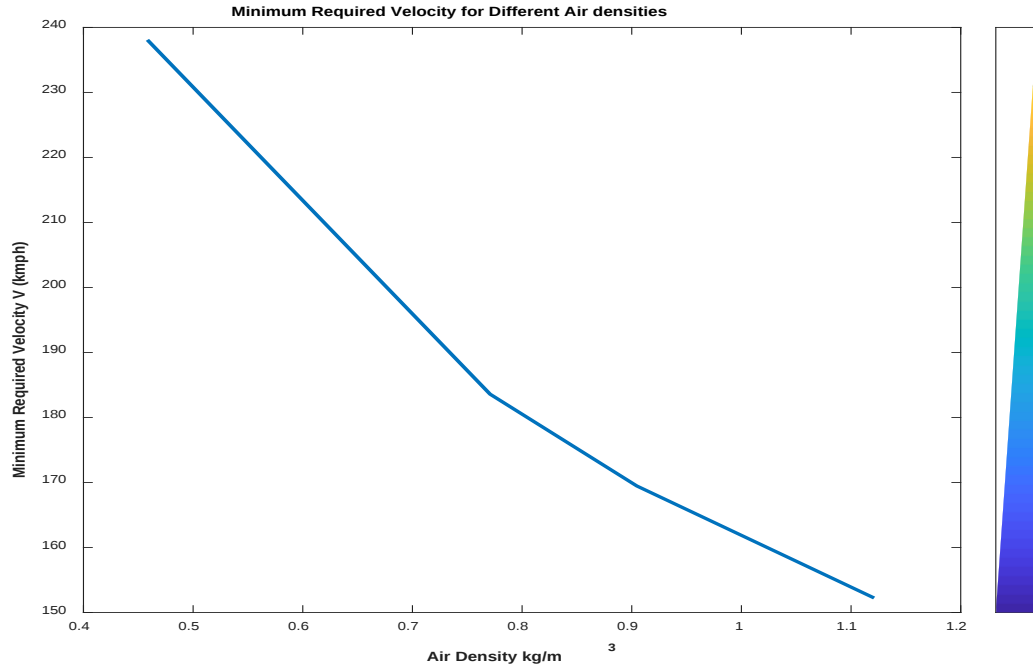


Fig: 5.3 Minimum required velocity vs Air density

5.2 HTS Racetrack Coil Property Simulation

The second most important factor in designing an electric aircraft is its power system. As it was said in chapter 3, for our design we are using 1MW HTS electric motor to power the turbines or turbofan. HTS motor is chosen due to its high efficiency and small size. The effect of size on aircraft performance is beyond the scope of this thesis. But the efficiency of the overall motor is calculated in chapter 3 and one of the major reason for this is the materialistic property of our desired HTS material which is YBCO.

For a material to show superconductivity characteristics it should have negligible resistance. YBCO resistivity is defined by the formula is defined by equation 5.3 which was experimentally determined in [22].

$$0 \quad |J| < J_c$$

$$E(J) = E_0 \times \left(\frac{|J| - J_c}{J_c}\right)^\alpha \quad |J| > |J_c|$$

Here

$E(J)$ = Electric field

J = Current density

α = Material constant

J_c = Criticla current density

The constant for this equation is given in table 5.4 and the values are taken from [22]. This equation is inserted in COMSOL and the resultant graph is shown in fig 5.4. As shown in the fig the electric field of the material remains 0 unless J dose not exceed J_c which is around 17MA which means that the electron flowing through the material is experiencing no resistance at all. Moreover, the critical current density value is much larger than the current that is needed for the HTS motor to operate so it's valid to assume that the motor will function in its superconductive nature all the time. The overall surface current density is given in fig: 5.5

E_0	100 μ V/m
α	1.449621256
J_c	17MA

Table: 5.4 Parameters for equation 5.3

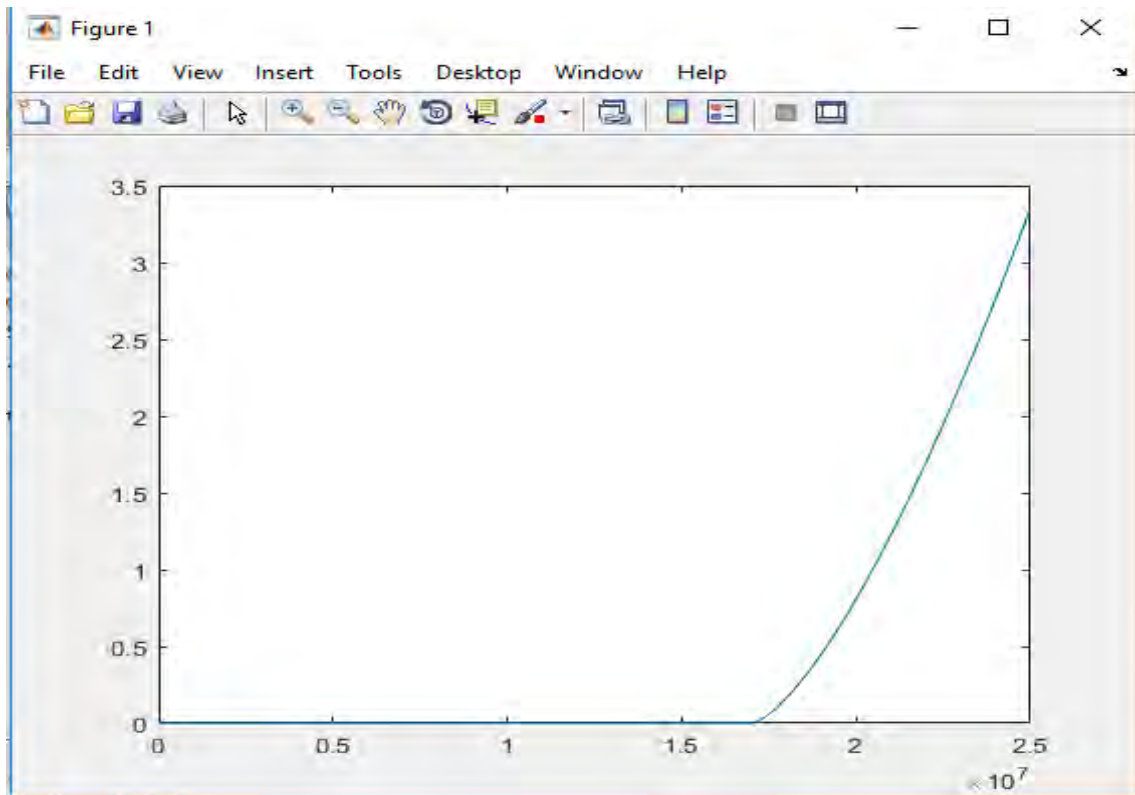


Fig: 5.4 Electric Filed vs Current Density

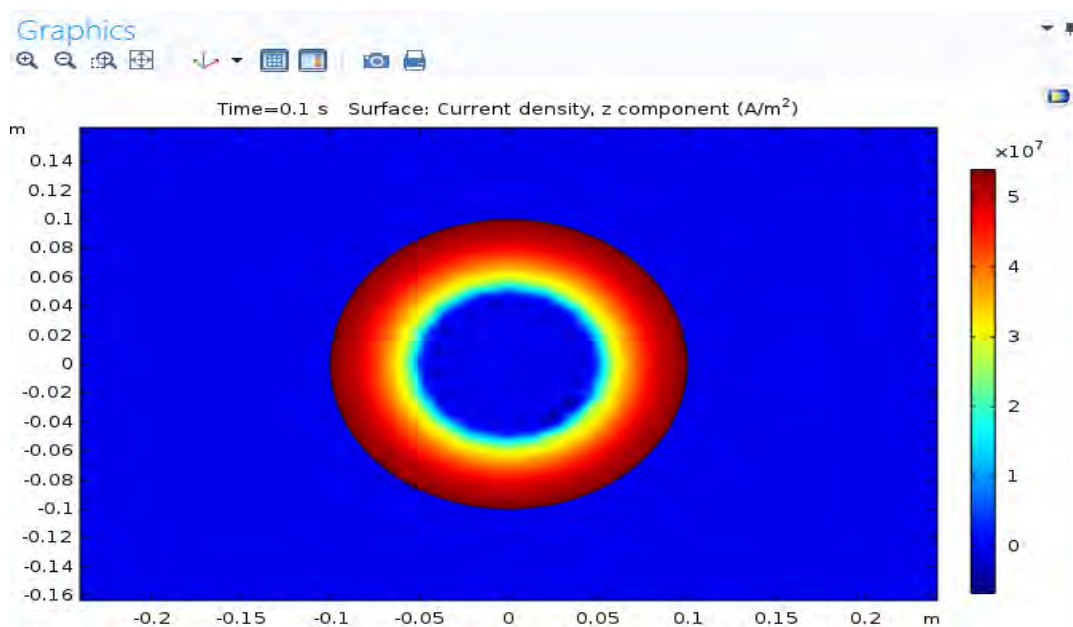


Fig: 5.5 Surface current density

The second factor relating to higher efficiency is the current density and its dependence on magnetic field density. By definition current density is the amount of current per unit area so size of the wire also has an effect in power output. According to equation 3.1 and 3.2 the current density depends both on the x and y component of B.

$$J_c(B) = \frac{J_{c0}}{1 + \frac{B_y}{B_0}}$$

$$J_c(B) = \frac{J_{c0}}{1 + \frac{B_x}{B_0}}$$

The overall effect of the magnetic field in 3 dimension is given in fig 3.13. Separately the effect of y component of B on J is given in fig 5.6 and for x component the graph is same only the direction changes. This simulation was done in MATLAB and it shows that with decreasing current density the magnetic flux increases. This is beneficial as the value of n (anisotropic property) decreases with increasing B and this effects the overall resistivity of the material. The variation of surface magnetic flux density in the HTS wire is given in fig: 5.7.

The resistivity of HTS material is given in equation 3.4 and from that it can be seen that with increasing value of n, ρ (resistivity) increases since it has a power law relation. The simulated results is shown in fig 5.7. When a low value of normalize current the resistivity is small. This is due to the fact as current density decreases, B increases which reduces the value of n which is desirable in our case.

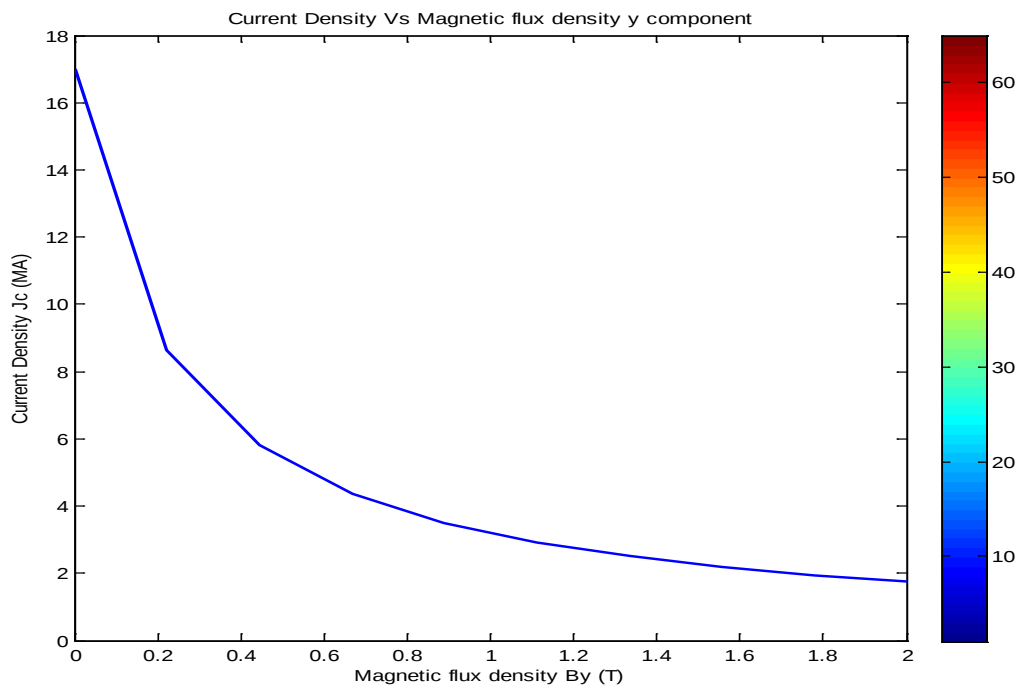


Fig: 5.6 Current density vs Magnetic Flux density

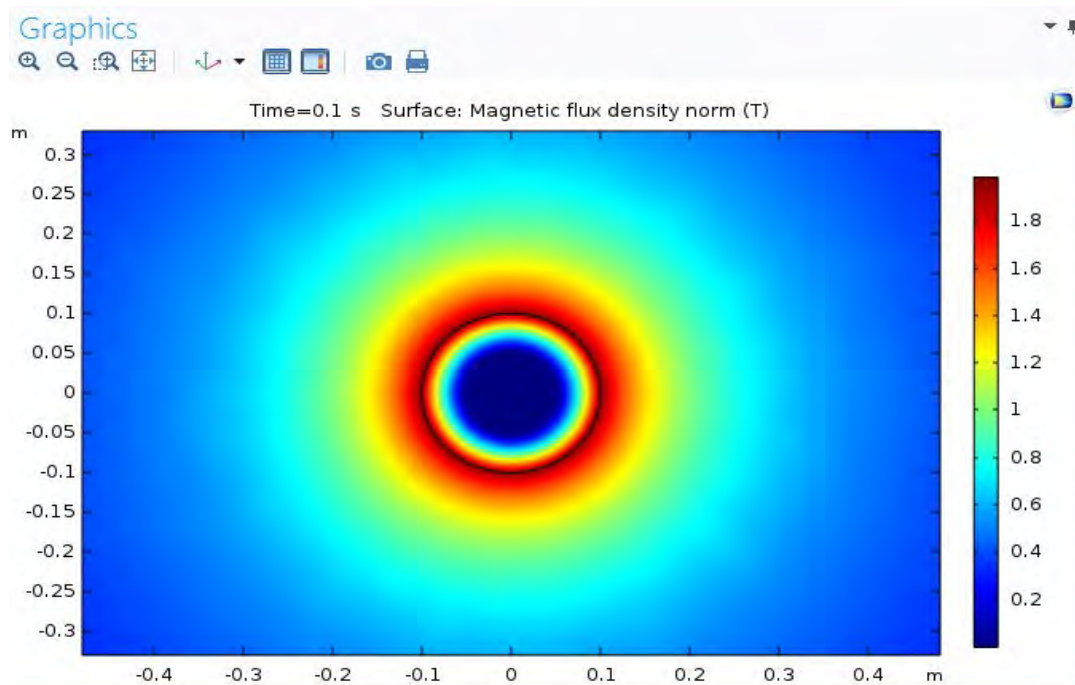


Fig: 5.7 Variation of surface magnetic flux density

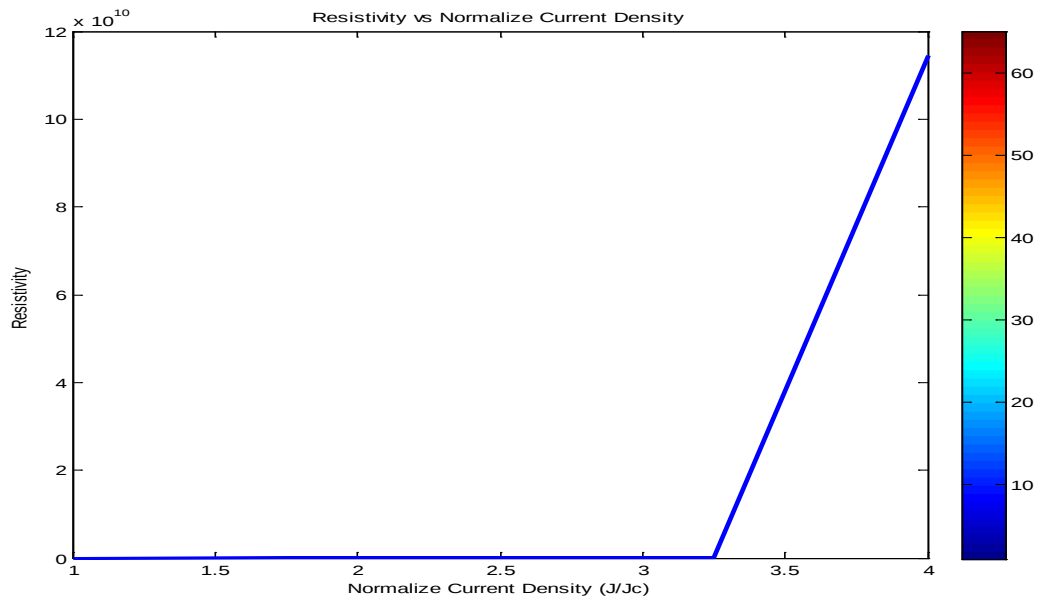


Fig: 5.8 Resistivity Vs normalize current

Table 5.5 shows the percentage difference between the simulated efficiency and the therotical efficiency.

Power	Simulated Efficiency	Therotical efficiency	Percentage difference
1MW	97.1	98%	0.92%
1.25MW	95.43	97.2%	1.82%
1.5MW	93.13	94.2%	1.13%

Table: 5.5 Percentage difference between the simulated efficiency and the therotical efficiency

$$\text{Percentage difference (1MW)} = \frac{98-97.1}{98} \times 100 = 0.92\%$$

$$\text{Percentage difference (1.25MW)} = \frac{97.2-95.43}{97.2} \times 100 = 1.82\%$$

$$\text{Percentage difference (1.5MW)} = \frac{94.2-93.13}{94.2} \times 100 = 1.13\%$$

5.3 Cryocooler Simulation & Comparison With MATLAB Results

For cooling system, cryocooler is used for engine. As the electrical aircraft has the hts motor [27] and the temperature is more than the commercial aircraft engine, the power of cooling system needs to be more effective to make cool the engine quickly to avoid any kind of incident.

Input Power: For our thesis we are using 9 MW system power and the superconductor that we are using is YBCO (Yttrium Barium Copper Oxide) conductor. To calculate the Input power [28] we are using an equation 5.4 given below which is related to the critical temperature of the conductor and highest temperature that can operate.

$$Pin = \frac{Qc}{\eta_{fc}} \frac{Th - Tc}{Tc}$$

Here,

η_{fc} = Carnot efficiency which is considered 0.3, by which we can achieve till 3 kg/kW.

Tc = Critical Temperature. For YBCO Tc is 60 k.

Th = Highest temperature that conductor can operate. For YBCO Th = 300.

Qc = system power. Our system power is 9 MW/ Engine.

As we are using two engines in our aircraft, the total system power will be 18 MW. For Different Th , we get different input power. The table is given below:

Tc (k)	Th (k)	Qc (MW)	Pin (kW)
60	111	18	51
60	175	18	115
60	250	18	190
60	300	18	240

Table: 5.6 Parameters for equation 5.4

These values are simulated in MATLAB and fig: 5.9 shows a linear relationship between input power power and temperature.

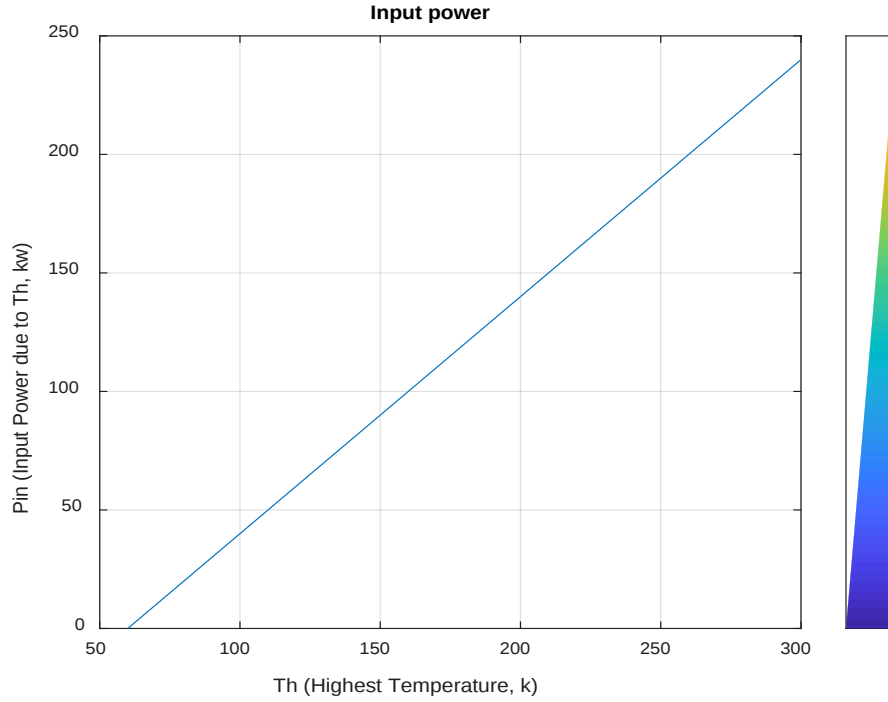


Fig: 5.9 Pin vsTh

Mass of the cryocooler: The mass of the cryocooler [8] depends on the input power which is depends on the temperature of the conductor. To get the mass of the cryocooler can be calculated by the equation given below:

$$M_{cryo} = 27.5e^{-1.225(\log_{10} Pin)}$$

Here,

M_{cryo} = Mass of the Cryocooler;

Pin = Input Power;

M_{cryo} is the specific mass in kg/kW of the whole cryocooler including heat exchangers, compressors, piping and insulation, and Pin is the cryocooler total input power requirement in kW. For different input power we get different masses of the cryocooler. Those are given below:

Th (k)	Qc (MW)	Pin (kW)	Mcryo (kg)
111	18	51	222.73
175	18	115	343.28
250	18	190	448.39
300	18	240	507.74

Table: 5.7 Different input power for different masses of the cryocooler

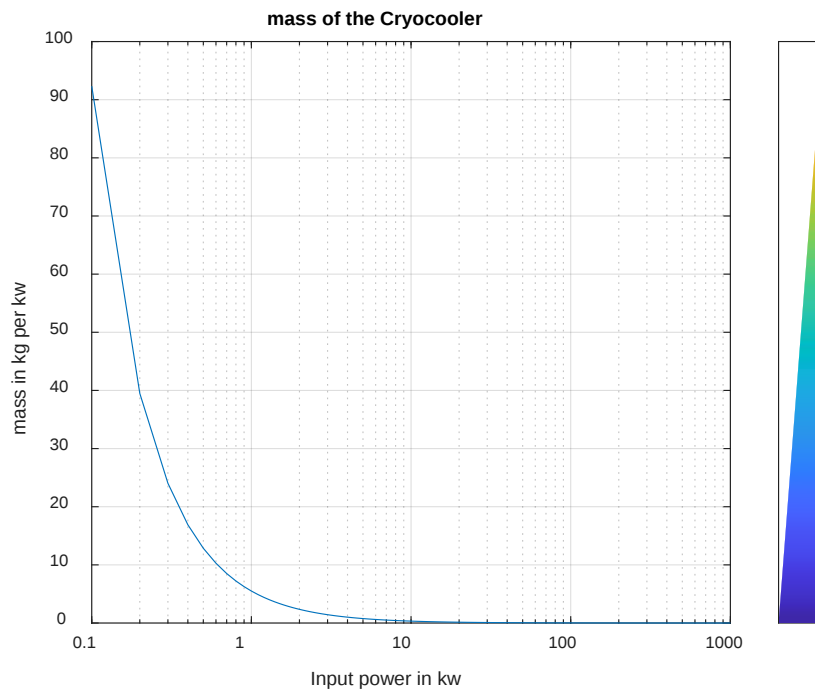


Fig: 5.10 Mass vs Input power

Chapter 6

Conclusion & Future Work

6.1 Conclusion

The goal of this work was to test the feasibility of an electric aircraft. This was achieved by studying the aircraft body structure, its electric power system and the cooling method used for the motor. The design of the whole project is beyond the scope of this thesis so only the theoretical study and the simulated results (in software like ANSYS and COMSOL) are compared with the theoretical value from various literature. The preferred model for the body is aurora D8 (project under NASA) which is still in development stage. Therefore, in this paper we have simulated (in ANSYS) how the angle of attack varies with speed and our value is nearly matches with the theoretical value found in [49]. This validates that with aurora D8 configuration the aircraft will have higher speed. The next part that is focused in this thesis is the electric power system. HTS motor are used to propel the aircraft. The HTS material used is YBCO and by inserting its property in COMSOL the transport current loss in armature is calculated. Using this loss the efficiency is determined. The percentage difference between the experimented values in [14] with our simulated value is below 2%. The reason for choosing this kind of motor is due to this high efficiency and smaller weight. One of the major challenge to operate this HTS motor is the cooling system (cryocooler) needed. So different type of cooler are studied and for RBCC cryocooler the simulation is carried out in ANSYS by changing the coolant. The final part of this report contains the comparison of ANSYS result with the MATLAB results.

6.2 Future Work

This thesis concludes that using HTS motor in D8 with RBCC cryocooler is suitable for an electric aircraft. However, further works is needed to conceptualize the whole aircraft. First the use of what type of battery should be used for running the motor. Here, only the armature was replaced with HTS material, hence further work can be done on fully HTS motor and calculating the loss. The idea of aurora D8 is still under research so until further research full validation is not possible. Moreover, all the values are simulated in software since here it is not possible to practically verify the results our self.

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