DEVELOPMENT OF CORRELATIONS FOR THERMO-PHYSICAL PROPERTIES OF SUPERCRITICAL HYDROGEN IN HIGH TEMPERATURE SUPERCONDUCTING GENERATOR

DISSERTATION II

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PUNJAB

CANDIDATE'S DECLARATION

This is to certify that the Thesis titled "**Development of correlations for thermo-physical properties of Supercritical Hydrogen in High temperature Superconducting Generator"** that is being submitted by "**S.Mugilan**" is in partial fulfillment of the requirements for the award of **Master of Technology Degree (Thermal Engineering)**, is a record of bonafide work done under my/our guidance. The content of this dissertation, in full or in parts, have neither taken from any other source nor have been submitted to any other Institute or university for award of and degree or diploma and the same is certified.

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Objective of the Thesis is satisfactory /unsatisfactory

Examiner I **Examiner II**

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ABSTRACT

The storage and generation of power has been a main objective over the past decade. To accomplish such an objective, superconductors are introduced in 1978, which observed a sublime growth in power generation systems. However, electrical losses such as AC losses and thermal losses due to conduction, convection and radiation in those superconductors are inevitable. In order to overcome and reduce these losses, use of cryogenic fluids above their critical temperature is necessary. One such fluid being studied in this work is supercritical hydrogen (SCH). Various thermophysical properties such as density, viscosity, thermal conductivity and specific heat of SCH were studied. The results reveal that with the rise in temperature there is a radical change in thermophysical properties of SCH. Besides, few correlations have been developed for the same at various pressures and temperatures. The developed correlations are elaborated such that, the use of supercritical hydrogen (SCH) may be explored in the HTS generator for improving its performance. These correlations can be employed for further research and advancement in HTS generators. Due to the dynamic nature of HTS generators, unlike HTS cables, the cooling requires careful attention and precise monitoring. With the use of SCH, a uniform temperature distribution in HTS generators is expected leading to higher efficiency.

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Nomenclature

T_c	Critical Temperature
I_c	Current flowing through coils
P_c	Critical Pressure
T	Temperature
F	Degree of Freedom
C	Number of constituents
G	Thermodynamic Potential
U	Internal Energy
ℓ	Density
S	Entropy
C_P	Specific Heat at constant pressure
$Ϗ_t$	Isothermal Compressibility
Γ́	Cofactor
Ɛ	Reduced Temperature
ʟ	Correlation length
κ	Thermal Conductivity
ʋ	Viscosity
ɑ	Thermal Diffusivity
$ℓ_C$	Critical Density

1.1 INTRODUCTION

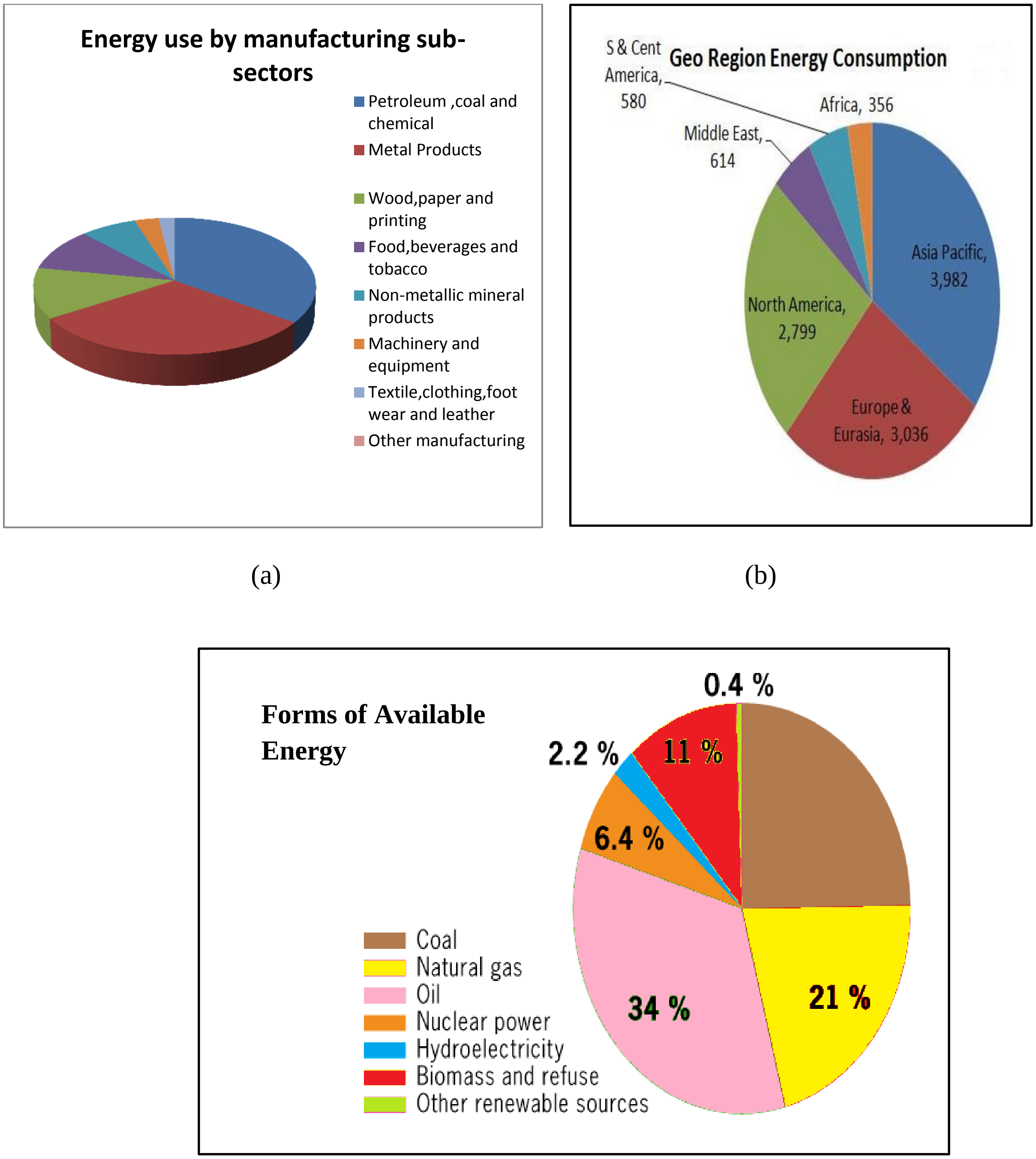
An effective method for storage and utilization of energy has been a major concern over the past decade in the field of conventional generators. Over the last century, the energy storage industry has continued to evolve and adapt to changing energy requirements and advances in technology [1, 2, 3, and 4]. Despite providing a wide range of technological approaches to managing our power storage and transmission, the losses incurred in these utility is inevitable [5, 6]. An introduction of superconductors in energy storage and transmission is one such case which provides solitary solution. Moreover, to maintain the resilience of such superconductors a coolant is required .And hence a proposal of utilization of supercritical fluids as coolant is put forth in this work. The major reason for implementing supercritical fluids is its maximum heat absorption capability. This chapter elaborates the description and importance of superconductors in energy storage, and also the need for implementing supercritical fluids in it. With uncovering the thermophysical properties of supercritical hydrogen (SCH) to be utilized in HTS generators. Due to the reduced size, weight and higher power system stability HTS generators were preferred over conventional generators. The current work was carried out due to need for improvement in HTS generators. For developing long life of HTS generators, SCH with desirable properties are being considered and subjected to further scrutiny for replacing conventional coolants. Various thermophysical property data of SCH were obtained and then plotted. Over the years, research on the supercritical fluids in HTS generators has been extensively performed. Comprehensive literature reviews of earlier studies on supercritical fluids can be found in [8, 9, 10, 11, 12] and HTS generator and motor in [13, 15, 16, 18]. A majority of previous works and more recent experimental and numerical studies concerning supercritical hydrogen [20, 21, and 22] indicate that temperature distribution over a prolonged region is uniform. The effectiveness of SCH in HTS generators could be significantly influenced by the active characteristics of hydrogen. The work carried out in this paper is an approach to estimate the various thermophysical properties with the help of correlations and comparing the obtained results with the standard NIST [7, 14] web book data. Though there have been significant research work carried out in the field of supercritical fluids, the concentration on SCH is minimal.

1.2 ENERGY STORAGE

The prime word energy has been acquired / derived from the ancient word (i.e.) Ancient Greek: ἐνέργεια energeia “activity, operation”, which perhaps seems to be the first time in the work of Aristotle in the 4th century BC. In 1807, Thomas Young was probably the first to use the term "energy" in its place of vis viva, in its modern sense. Gustave-Gaspard Coriolis defined "kinetic energy" in 1829 in its contemporary intellect, and in 1853, William Rankine invented the term "potential energy". The law of conservation of energy, was also first suggested in the early 19th century, and applies to any remote system. It was contended for some years whether heat was a physical substance, entitled the caloric, or merely a physical quantity, such as momentum. In 1845 James Prescott Joule discovered the link between mechanical work and the heat generation. Energy is an asset of objects, exchangeable among them via fundamental interactions, which can be altered into one form, but neither, can be created nor destroyed. The SI unit of energy is joule, based on the amount transmitted to an object by the mechanical work of moving it 1 metre against a force of 1 newton.

Energy is one of the most important inputs for economic growth and human development. Effective energy utilization determines the world’s growth in financial, technological, environmental and civilization. There is a solid mutual relationship between economic development and energy consumption. On one hand, the economy growth, with its global competitiveness, pivots on the availability of cost effective and environmental friendly energy sources, and on the contrary, the level of economic development has been observed to be dependent on energy demand.

The energy needs of the country are expected to escalate at a rapid rate in the upcoming years. Hence, it is vital to take necessary steps to escalate the available energy resources so as to avoid too much dependence on external sources. Nuclear, hydel energy, as well as non-conventional sources of energy is the options available in terms of energy, also need to be completely observed into. In meeting energy needs Non-conventional sources of energy may come into play an increasing role, particularly of the rural population, which rest on mostly non-commercial sources of energy. Admittance to affordable and inexpensive energy promotes growth in all sectors of the economy such as industry, transport, and is thus a crucial necessity for confirming affordability.



(a) (b)

(c)

Figure 1 (a),(b),(c) Energy Distribution Chart [1]

The above chart depicts the energy consumption, sources and utilities from across the globe. All these aspects contribute to the importance of storage of energy. The availability of energy in the form of various sources paves way for numerous applications, such as industrial, household, etc. The below chart shows the conversion of energy into useful work in a general working system, which shows only 60% energy has been converted into useful work and remaining is lost in form of various losses. And hence there arise a need for energy conservation and complete utilization of the same.

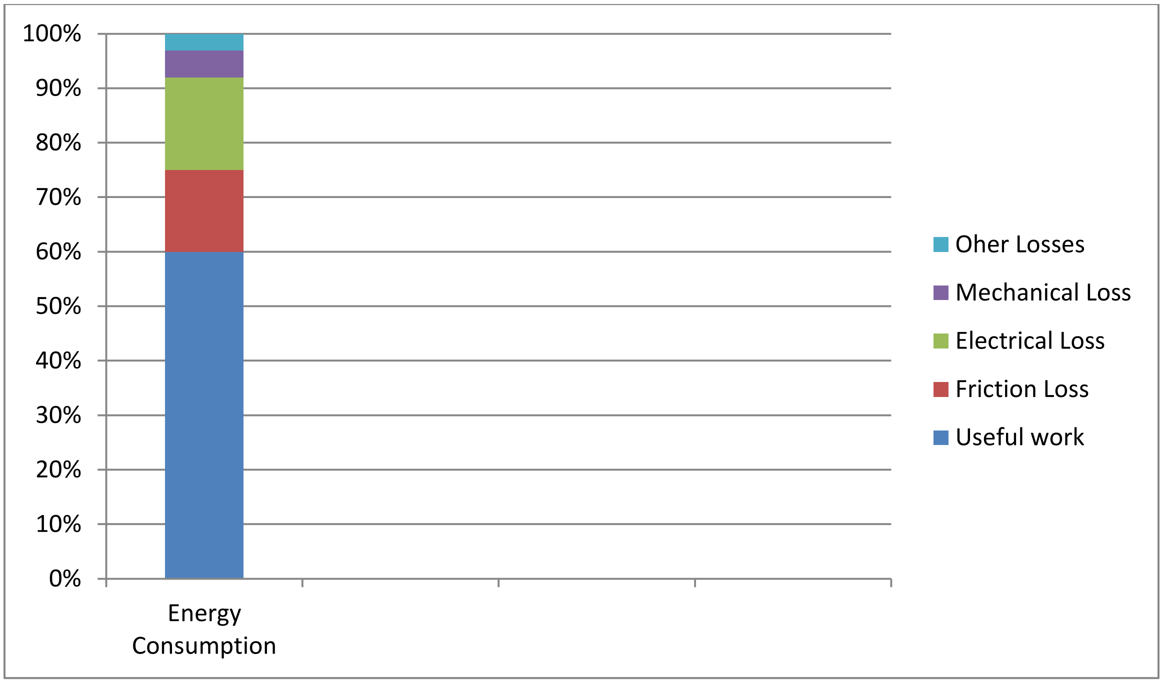


Figure 2 Complete Energy Utilization in a System [1]

The primary stages of energy development headed towards the theory of conservation of energy, famed largely by William Thomson (Lord Kelvin) as the field of thermodynamics. Thermodynamics was aided by the rapid development of explanations of chemical processes by Rudolf Clausius, Josiah Willard Gibbs, and Walther Nernst. It also led to a mathematical formulation of the concept of entropy by Clausius and to the introduction of laws of radiant energy by Jožef Stefan. According to Noether's theorem, the conservation of energy is a consequence of the fact that the laws of physics do not change over time. Thus, since 1918, theorists have understood that the law of conservation of energy is the direct mathematical consequence of the translational symmetry of the quantity conjugate to energy, namely time. On one hand, the economy growth, with its global competitiveness, pivots on the availability of cost effective and environmental friendly energy sources, and on the contrary, the level of economic development has been observed to be dependent on energy demand.

In modern world where energy crisis is deep rooted into the production scenario, various other options in the form of alternating energy sources are to be developed. But to overhaul the remaining energy in the world alternative measures in the form of superconductors are to be implemented. Insufficient energy problems are to be solved with the advent of superconducting device and controls.

2.1 SUPERCONDUCTORS

A material that can conduct electricity or transport electrons from one atom to another with no resistance is termed as superconductor. This means no heat; sound or any other form of energy would be released from the material when it has reached "critical temperature" (T_c), or the temperature at which the material becomes superconductive.

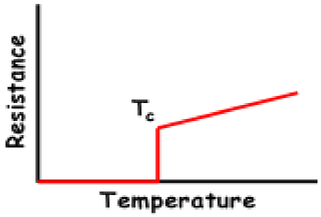


Figure 3 Characteristic curve showing Critical Temperature [5]

2.2 SUPERCONDUCTIVITY

Superconductivity is a phenomenon of exactly zero electrical resistance and exclusion of magnetic fields when cooled below a characteristic critical temperature. It was discovered by Dutch physicist Heike Kamerlingh Onnes on April 8, 1911 in Leiden. Superconductivity is a quantum mechanical phenomenon, which is characterized by the Meissner effect, the complete rejection of magnetic field lines from the interior of the superconductor as it transits into the superconducting state.

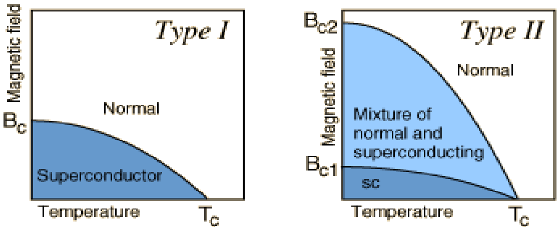


Figure 4 Type I and Type II superconductor state [5]

2.2.1 Type I Superconductor

The Type 1 category of superconductors that show some conductivity at room temperature is mainly comprised of metals and metalloids. They require irrational cold to slow down molecular vibrations sufficiently to facilitate unrestricted electron flow in accordance with what is known as BCS theory. BCS theory suggests that electrons team up in "Cooper pairs" in order to help each other overcome molecular. This process is called phonon-mediated coupling because of the sound packets generated by the flexing of the crystal lattice.

Type 1 superconductors are characterized as the "soft" superconductors which require the coldest temperatures to become superconductive. They exhibit a very sharp variation to a superconducting state and "perfect" diamagnetism - the ability to repel a magnetic field completely.

2.2.2 Type II Superconductors

A type II superconductor is poised of metallic compounds such as copper or lead. They reach a superconductive state at much higher temperatures when linked to type I superconductors. Type II superconductors can also be pierced by a magnetic field whereas a type I superconductor can't.

Superconductors form a basis on Meissner effect, which put forth the concept and ideology of superconductivity.

2.3 MEISSNER EFFECT

The Meissner effect is the eviction of a magnetic field from a superconductor during its shift to the superconducting state. The German physicists Walther Meissner and Robert Ochsenfeld discovered this phenomenon in 1933 by assessing the magnetic field distribution outside superconducting tin and lead samples. The samples, in the presence of an applied magnetic field, were cooled below their superconducting transition temperature. Below the conversion temperature the samples cancelled nearly all interior magnetic fields. They detected this effect only indirectly because the magnetic flux is conserved by a superconductor: when the interior field decreases, the exterior field increases.

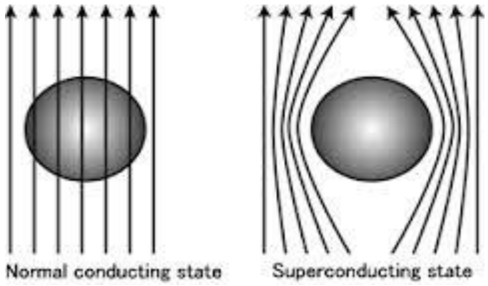


Figure 5 Meissner Effect [2]

- **Critical temperature (T_c),** the normal conductor losses its electric resistivity and converts into a superconductor at this temperature. And hence, this statutory region or point is known as critical or transition point [6]. The critical temperatures of different cryogenic coolants and superconductors are shown below.

Table 2 Different cryogens and superconductors Critical temperatures [6]

Critical Temperature, T_c (K)	Superconductors and Cryogens	
5.195K	Helium, He	
33.19K	Hydrogen, H_2	
126.190K	Nitrogen, N	
150.690K	Argon, Ar	
154.580K	Oxygen,O_2	
90.0K	YBCO	HTS (High Temperature Superconductors)
110.0K	BaSrCaCuO	
118K	TiSrCaCuO	
134.1K	HgBaCaCuO	

3.720K	Strontium, Sn	LTS (Low Temperature Superconductors)
4.15K	Mercury, Hg	
7.190K	Lead, Pb	
10.0K	Neodymium, Nb	

- **Critical current (I_c),** with zero electric resistance when the extreme value of current that flows through the superconductor then it is called critical current. The superconductor behaves as a normal conductor above this point [6].
- **Critical magnetic field (H_c),** when a superconductor behaves as a normal conductor above a critical point or transition state. The superconductor turns out to be a normal conductor if the magnetic field is large therefore [6]. The relation for the critical temperature and magnetic field [8] is expressed as

$$H_C = H_0\left[1-\left(\frac{T}{T_C}\right)^2\right] \tag{1}$$

Where

H_o = Critical field at 0K,

H_c = Critical Magnetic field,

T= Temperature below critical temperature T_c.

According to their critical temperatures, the superconductors are classified are as follows:

- Low Temperature Superconductors (LTS)
- High Temperature Superconductors (HTS)

2.4 HIGH TEMPERATURE SUPERCONDUCTORS

The materials which is having critical temperature (T_c) >30 K are called High Temperature superconductors (HTS)[6]. First HTS material was found in LaBaCuO and its critical Temperature is 32 K in the year 1980-1990. The development of HTS has enlarged its critical Temperature to 240 K at present [6].

- Advantages of HTS
  1. Very much Compact in Size
  2. losses are Low
  3. large current carrying capacity
- Applications of HTS
  1. Power transmission Cables
  2. Transformers
  3. Motors
  4. Generators
  5. Superconducting Magnetic Energy Storage (SMES)

2.5 LOW TEMPERATURE SUPERCONDUCTORS

The materials which is having critical temperature (T_c) <30K are called Low Temperature Superconductors (LTS)[6]. Superconductivity occurs in pure metals such as mercury and lead which are known as LTS, which was discovered by H. Kammerlingh Onnes in the year 1911.

- Applications of LTS
  1. Magnet

2.6 GENERATORS

There are two simple types of generators: "Conventional" and "Inverter" generators. The Conventional Generator has been around for a very long time. It is mainly a motor attached to an alternator that produces AC or DC energy. They consist of an energy source, usually a fossil fuel such as diesel, propane or gasoline, which powers a motor attached to an alternator that produces electricity. The motor must run at a constant speed (usually 3600 rpm) to produce the standard current that is required.

2.6.1 HTS generators

When compared to conventional generators of comparable size, HTS generators provide improved efficiency thereby reducing machine losses by as much as 50 percent. In addition, HTS generators are considerably smaller and lighter than conventional machines (generators). In a ship environment where space and weight are at top priority, these advantages are very attractive. One of the biggest knockers to reliability and life expectancy of conventional rotating machines are its thermal cycling and heat. By operating at a near constant cryogenic temperature HTS rotating machines virtually exclude these failure modes.

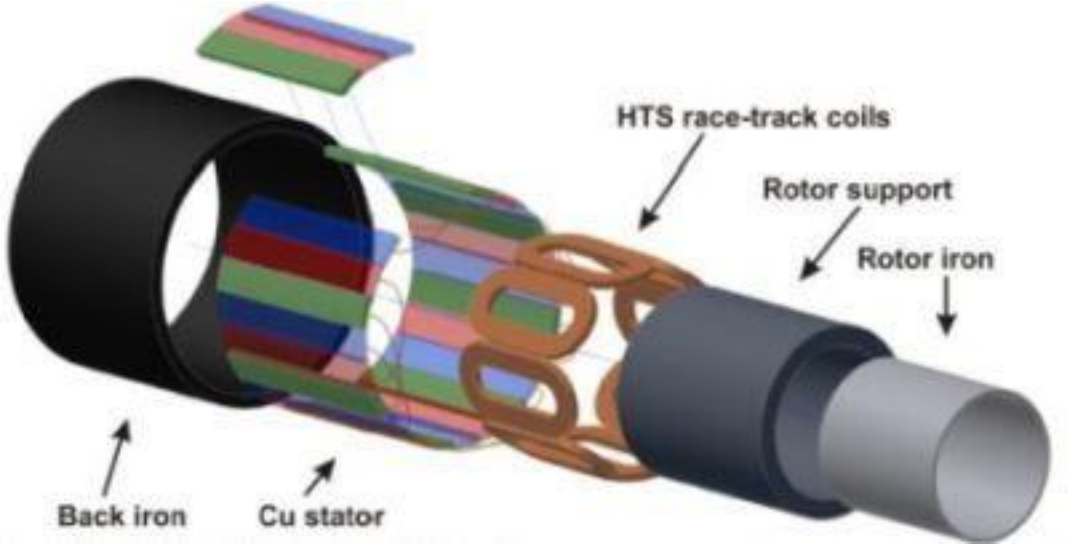


Figure 6 Cross-Sectional view of HTS Generator [15]

A typical superconducting generator configuration consists of the rotor with the HTS field windings spinning inside the stationary windings (stator) that surround the rotor core. The HTS field windings will originally operate in the DC magnetic field of up to 4 Tesla with temperature range of 25 to 40 Kelvin. The rotor assembly is typically cooled to cryogenic temperatures whereas the stator windings are maintained at ambient conditions. The field coils located on the rotor are cooled by a commercially available cryocooler system using either liquid or cold gas as the heat transfer medium. As the magnetic field produced by the rotor field windings cuts across the turns of wire in the stationary coils, an electric current is set up in the wire. In a three phase generator, there are usually three separate stator windings, each producing its own separate single-phase voltage. Since these windings are staggered around the generator circumference, each of the single-phase voltages is "out of phase" with one another.

2.7 SUPERCRITICAL FLUIDS

A supercritical fluid is any element at a temperature and pressure above its critical point, where discrete liquid and gas phases do not occur. It can effuse through solids like a gas, and dissolve materials like a liquid. On contrary, close to the critical point, small changes in pressure or temperature result in huge changes in density, allowing many properties of a supercritical fluid to be "fine-tuned". Supercritical fluids are suitable as a supernumerary for organic solvents in an array of industrial and laboratory processes. Water is the most frequently used supercritical fluids for power generation. In 1822 Baron Charles Cagniard de la Tour discovered supercritical fluids while performing experiments involving the incoherence of the sound of a flint ball in a sealed cannon barrel filled with various fluids at various temperatures. Liquefying the matter using any amount of pressure is impossible since the supercritical fluids have the low viscosity of a gas and the high density of a liquid. However, just by lowering the temperature of the liquid, it is possible to drive from a gas to a liquid without crossing the boundary between the vapor and liquid phase using a supercritical fluid. Volatile liquids and solids, or liquids and solids with a high vapor pressure or low boiling point, are soluble in gas. Because of the high density it becomes especially easy to dissolve liquids and solids such as these in a supercritical fluid. Supercritical fluids have no surface tension because they are not subject to the vapor-liquid boundary so no molecules have the attraction to the interior of the liquid. The densities and viscosity of a supercritical fluid are subject to alter when pressure or temperatures are damaged with, and the supercritical fluid of a substance can have very different properties than the regular fluids. For instance, water that is supercritical differs from regular water in the fact that it is non-polar and acidic. To understand what happens at the critical point, consider the effects of temperature and pressure on the densities of liquids and gases, respectively. As the temperature of a liquid increases, its density decreases. As the pressure of a gas increases, its density increases. At the critical point, the liquid and gas phases have exactly the same density, and only a single phase exists.

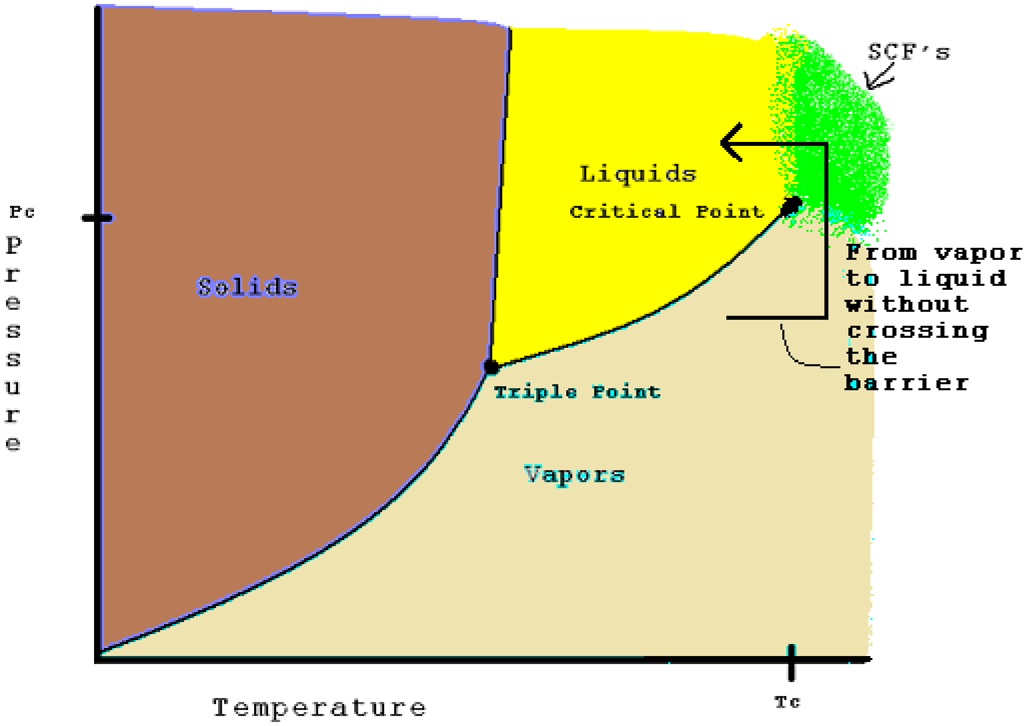


Figure 7 Characteristic curve depicting supercitical state [3]

2.7.1 Supercritical hydrogen

Discovered by Henry Cavendish in 1766, hydrogen be indebted its name to Lavoisier, who united the Greek hydor, water, and genen, to engender. It is the lightest gas in the world and therefore is not seized by the earth's solemnity. Hydrogen is established in the atmosphere at smidgen levels; it is synthetized from hydrocarbons (petroleum and by-products of petroleum) and from water where it constitutes the lightest fraction of the H_2O molecule. Hydrogen gas characteristics include colorless, highly flammable, very light, cannot endure life and reacts effortlessly with other chemical substances. Hydrogen is a fresh energy transferor. Used in a fuel cell, it associates with oxygen to efficiently yield electricity and doesn't emit anything except water. To occur as a liquid state, hydrogen must be cooled below its critical point of 33.19 K. However, for hydrogen to be in a completely liquid state without evaporating at atmospheric pressure, it needed to be cooled to 20.28 K. Liquid hydrogen is typically used as a resolute form of hydrogen storage. As in any gas, storing it as liquid takes a lesser amount of space than keeping it as a gas at normal temperature and pressure. However, the liquid density is very low compared to other common fuels. Once liquefied, it can be very well maintained as a liquid in pressurized and completely well furbished thermally insulated containers.

Hydrogen Properties

- Molecular weight : 2.0159 g/mol
- Melting point : -259.2 °C
- Liquid density (1.013 bar at boiling point) : 70.849 kg/m^3
- Boiling point (1.013 bar) : -252.78 °C

Critical point

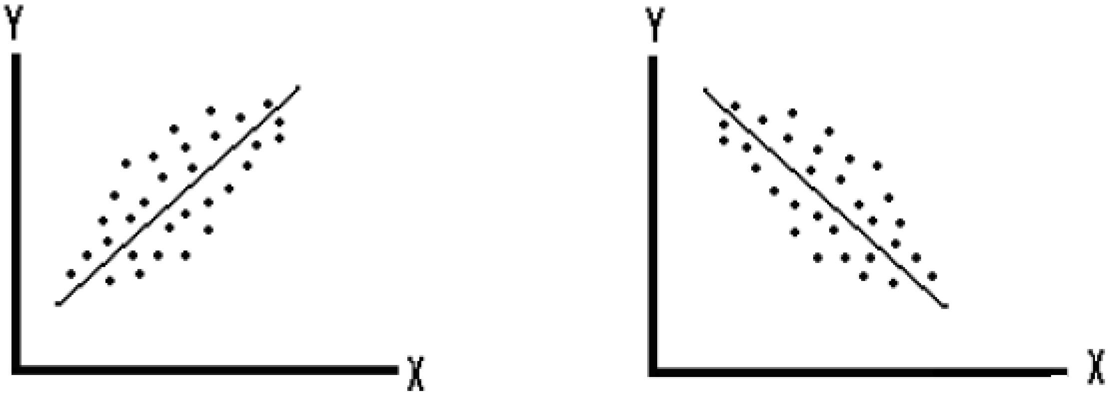
- Critical temperature : -240.01 °C
- Critical pressure : 12.96 bar
- Critical density : 31.263 kg/m^3

Triple point

- Triple point temperature : -259.19 °C
- Triple point pressure : 0.077 bar

2.8 CORRELATION

The correlation is one of the most communal and most convenient statistics. The degree of relationship between two variables can be described by a single correlation. Correlation is a statistical technique that can show whether and how strongly pairs of variables are related. For example, in a system of heat generation temperature and pressure are related. Temperature and pressure varies at frequent interval and it is difficult to keep track of it, due to its imperfect affiliation. Correlation can express just how much of the variation in heat generation is related to their system. Although this correlation is fairly obvious the specified data may contain unsuspected correlations. It may also be suspected that there are correlations, but difficult to know which are the resilient. An intellectual correlation analysis can lead to a greater understanding of the proposed data.



Positive Correlation

Negative Correlation

Figure 8 Positive and Negative Correlation Graph [9]

Empirical study portrays that efficiency of high-temperature superconducting (HTS) generators is 98 percent more, and the losses are reduced considerably by 50 percent when compared to conventional generators. HTS generator indulges abridged pollution per unit of energy formed, lowers life-cycle cost, and reduces power losses with improved energy savings. Thus, the usages of superconducting generators are on the rise due to the zero electrical resistance and minimal power loss. The strong magnetic fields produced in this HTS generator leads to electric machines of high power density. However, the marginal losses are due to the advent of heat generated in the device. Thus, there is a need for optimization, which can be attained through the introduction of supercritical fluid as coolant. The introduction of supercritical fluid on the HTS generators might be the ideal solution for preventing the electrical losses in it.

CHAPTER 4 OBJECTIVE

The primary objective of this work is to

1. Make a detailed review on superconducting generator and it's characteristically behavior.
2. Optimize thermal insulation of the superconducting generators which is in need of an efficient refrigeration unit.
3. Study the behavior of various supercritical fluids, which can be implemented in the HTS generators for prolonged lifecycle of the same.
4. Develop a novel correlation for the designated supercritical fluid to be implemented in the HTS generator.

The main aim of development of correlations for super critical hydrogen to be used in HTS generators is to improve the performance characteristics of the same. The following literature review portrays the need for effective refrigerant to be installed in HTS generators.

G. N. Sapkale et al. [8] proposed that Supercritical fluid extraction was the most effective and efficient way to extract valuable constituent botanicals. Supercritical Fluid Extraction (SFE) was the process of separating one component from another (the matrix) using supercritical fluids that is CO2 as the extracting solvent. CO2 is the king of extraction solvents for botanicals. Extraction conditions for supercritical CO2 are above the critical temperature of 31°C and critical pressure of 74 bar. Supercritical fluids are highly compressed gases, which had combined properties of gases and liquids in an intriguing manner. Supercritical fluids can lead to reactions, which are difficult or even impossible to achieve in conventional solvents. It was a fast process completed in 10 to 60 minutes. A supercritical fluid can be separated from analyze by simply releasing pressure, leaving almost no trace and yields a pure residue.

P. Rios et al. [9] explained the potential of superconductivity for high current density and high magnetic fields has given rise to efforts to develop superconducting ac generators throughout the world. Superconductivity affords the only known means of substantially increasing power density while simultaneously reducing electrical losses in rotating electrical machines. Initially, development efforts were concentrated on small-scale component tests; the focus has now shifted towards larger-scale demonstrations of technical feasibility. This paper surveys recent changes in the status of the development of superconducting ac generator. The ongoing development program in the author's company is reviewed.

Seungkyu Baik et al. [10] proposed the superconducting motor shows several advantages, such as smaller size and higher efficiency, over a conventional motor, especially utilized in ship propulsion applications. However, the size reduction merit appears for large capacity, more than several MW. A large capacity synchronous motor with a rotating high-temperature superconducting (HTS) coil, that was aimed to be utilized for ship propulsion, so it had a low rotating speed of about 200 rpm. The ship propulsion motor must generate high electromagnetic torque instead of low speed. Therefore, the rotor (field) coils have to generate a large magnetic flux that results in a large amount of expensive HTS conductor for the field coil. In this paper a 17 MW HTS motor for ship propulsion was designed with a cost-effective method because the HTS conductor cost is a critical factor in the construction of an HTS motor. Unlike conventional rotating machines, the superconducting motor consists of an iron coreless. structure. Most conventional motors can be designed with small error based on two-dimensional magnetic field analysis. However, the superconducting motor shows an even larger error between the two- and three-dimensional based designs. Thus, in order to improve the design accuracy, it had calculated the back electromotive force (EMF) using 3D magnetic field analysis. An output performance evaluation had also been carried out to obtain a design with higher efficiency.

J.W. Bray et al. [11] examined present and future applications of superconductors. The host of requirements that must be satisfied for a successful commercial application were described and discussed briefly. The substantial role of materials in applications, the large number of requirements on successful commercial superconducting wire, and the trends in superconducting material development were discussed. Any paper about superconducting applications should not neglect to mention its necessary ally, cryogenics. All superconductors require cryogenic technology for any application. Description of this engineering field, in which most applications are apart from superconductors, is outside the scope of this paper.

Smith, J.L., Jr., et al. [12] described the superconducting synchronous generators were being developed world wide. Early results established the feasibility of these machines and showed that the best configuration was a rotating superconducting field inside a normally conducting armature in the stator. Extensive analytical development was providing a sound basis for the design of superconducting AC machines. Recent experimental results had demonstrated power density improvements over that of conventional generators. The designs developed by different groups were significantly different in the following areas: Rotor shielding and rotor structure; field coil support and construction; superconductor design; helium system design; and armature configuration. The development strategies of the groups have different emphases on basic engineering, development of components, and construction of prototypes. The major deficiencies of the programs were no full-load or full-fault testing.

R. Scott Oakes, et al. [13] paid interest to provide organic chemists with an up to date review of the use of supercritical fluids in synthesis. Because of the unusual nature of this reaction medium, an initial brief introduction on supercritical fluids (SCFs) was included to aid the understanding of the subsequent discussion of reactions. The major part of the review was centered on reactions which are likely to be of most interest to the synthetic organic chemistry community, with an emphasis on the most recent publications up to September 2000, and those examples which demonstrate the use of SCFs to be particularly advantageous. A number of previous reviews have been published in this area describing topics such as homogeneous catalysis, heterogeneous catalysis, and SCFs as solvent replacements in chemical synthesis. Other reviews are referenced in appropriate places throughout the text. There were also two recent books published in the area, one of which describes many aspects of synthetic chemistry in SCFs, whilst the other concentrates on more physical aspects.

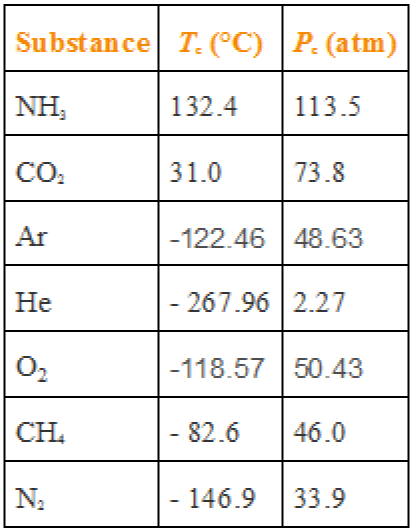
Minnich S.H., et al. [14] proposed an Electric Power Research Institute sponsored study of superconducting, central-station turbine generators of 300 and 1200 MVA rating had been completed at General Electric., superconducting field winding. The goal of this construction was to ensure that the winding can be energized to the current and flux density predicted by the superconductor short-sample data, without the "training" instabilities frequently encountered in 1arge coils. The remainder of the rotor components includes an aluminum radiation shield and a compound, steel-aluminum electromagnetic shield, designed to withstand short circuit electromagnetic forces. The study was focused on generator model configurations which were proportioned to have a low transient reactance, approximately 0.2 per unit. The critical clearing times calculated for these configurations were comparable to those of conventional units, the low reactance offsetting inherently lower rotor inertia. These generator configurations were estimated to have about half the size and weight, and about half the losses of conventional same rating. Transient characteristics were described, including the effect of the rotor shielding configuration on rotor dam.

Lambrecht.D, et.al [15] explain that due to technological progress over the last ten years, manufacturing long lengths of Nb-Ti ultra-fine filamentary wires with greatly reduced 50-60 Hertz losses had been achieved. The prospective industrial applications in large superconducting 50/60 Hertz equipment heralds promise of a technological revolution in electrotechnology. In this paper the author presents the results available on design and test machines used in electrotechnology. i.e., Classical A.C. machines with superconducting rotor windings (generators) and "Superconducting" 50/60 Hertz machines (transformers, generator armature windings).

Cesar A. Luongo, et.al [16] was proposed that sustainability in the aviation industry calls for aircraft that are significantly quieter and more fuel efficient than today’s fleet. Achieving this will require revolutionary new concepts, in particular, electric propulsion. Superconducting machines offer the only viable path to achieve the power densities needed in airborne applications. This paper outlines the main issues involved in using superconductors for aero propulsion. We review our investigation of the feasibility of superconducting electric propulsion, which integrate for the first time, the multiple disciplines and areas of expertise needed to design electric aircraft. It was shown that superconductivity is clearly the enabling technology for the more efficient turbo-electric aircraft of the future.

Paul N. Barnes, et.al [17] explained many future military systems will depend heavily on high electrical power input ranging from hundreds of kilowatts up to the multi megawatt level. These weapon systems include electromagnetic launch applications as well as electrically driven directed energy weapons (DEW), such as high-power microwaves and solid-state lasers. These power generation subsystems must often be packaged using limited space and strict weight limits on either ground mobile or airborne platforms. Superconducting generators made of high-temperature superconductors (HTS) will enable megawatt-class airborne power systems that were lightweight and compact. Also discussed briefly are new advances in HTS conductors and refrigeration systems furthering the development of HTS power systems.

Comprehensive literature review emphasizes the need for application of supercritical fluids on high temperature superconducting generators. Since the normal refrigerant could not withstand the increasing temperature and pressure developed inside the rotor of the HTS generator. The selection of suitable coolant for the refrigeration process can be made possible through SCH. Since critical temperature and pressure of SCH is less compared to the other SCF. The lower critical temperature (33K), critical pressure (1.314 MPa) and ease of availability makes SCH an ideal coolant for the HTS generators. The following table shows the critical temperature and pressure of various supercritical fluids. The following table shows the critical temperature and pressure of various liquid refrigerants and supercritical fluids.



Substance	**T_c (°C)**	**P_c (atm)**
NH_3	132.4	113.5
CO_2	31.0	73.8
Ar	-122.46	48.63
He	- 267.96	2.27
O_2	-118.57	50.43
CH_4	- 82.6	46.0
N_2	- 146.9	33.9

Table 2 Comparison of T_c and P_c for various elements [8]

Development of correlations provides an approach to calculate the thermophysical properties of SCH (Supercritical Hydrogen) with high accuracy compared with other empirical method using varying pressure and temperature. An illustration of correlation between the actual and the individual values of any quantity can be calculated using the above formulation.

$$\tau_{xy} = \sum_{i=1}^{n} (X_i - \bar{X})^2 (Y_i - \bar{Y})^2 / \sqrt{\sum_{i=1}^{n} (X_i - \bar{X})^2 \sum_{i=1}^{n} (\mathrm{Y}_i - \bar{Y})^2} \quad \text{---- (2)}$$

Where:

X and Y are variables

τ_{xy} is relation between X and Y

Σ is Sigma, the symbol for "sum up"

$(X_i - \bar{X})$ is each x-value minus the mean of x

$(\mathrm{Y}_i - \bar{Y})$ is each y-value minus the mean of y

The above formula is applied for different values of x and y, the values obtained is plotted and end result is obtained. Correspondingly in the case of supercritical fluid, the correlations developed determine the flow behavior of the supercritical fluid inside the HTS generator. Since, the work portrayed here is concentrated on the deployment of SCF on HTS generators, the importance of correlations which intern decides the flow behavior is inevitable, Graphs are being plotted with esteem to temperature ($T=T_c+50K$) and Pressure ($P=P_c+10bar$), besides the variation of thermophysical properties above its critical point. With due investigation, there is a radical variation in every thermophysical properties such as density, specific heat, thermal conductivity and viscosity in the supercritical region. So it turn into problematic to fit the curve with a single correlation, henceforth piecewise correlations are established in order to assess the thermo-physical properties with minimal standard errors and utmost accuracy. The various steps incurred in forming the correlations for the thermophysical properties of SCH are as follows.

In order to evaluate the thermophysical properties of SCH, two types of functional fits are used. They are: Rational fit (Equation.3), Polynomial fit (Equation. 4).

$$y = \frac{a + bx + cx^2}{1 + dx + ex^2} \quad \text{………………. (3)}$$

$$y = \sum_{i=1}^{n+1} p_i x^{n+1-i} \quad \text{..…………….. (4)}$$

Where

x = variable (independent)

y = variable (dependent)

a, b, c, d, e are the fitting constraints

n = degree of the polynomial ($1 \leq n \leq 9$)

(n+1) = order of the polynomial

In order to estimate the thermophysical properties of SCH these models are employed and they depict an exceptional concord during assessing the property values. Within a range of temperature variable, the property value changes drastically.

7.1 SUPERCRITICAL HYDROGEN (SCH)

For Supercritical Hydrogen (SCH) at critical pressure (1.312 bar) and for a temperature range of (33.190K – 83.19K) the correlations have been developed. For each thermophysical property such as density, specific heat, thermal conductivity and viscosity an entire data points of 500 are plotted in order to fit the curve. In the supercritical regime the variation in different thermophysical property values are observed when the desired property along (y-axis) and temperature along (x-axis) and above the critical pressure is plotted. Table 3 to Table 6 indicates that for all the four thermophysical Properties (thermal conductivity, density, viscosity, and specific heat) of SCH correlation coefficients for curve fits (Polynomial fit and Rational fit).

Table 3 Correlations Table for Density of Hydrogen in supercritical region

Temperature Range	**Correlation**	**Correlation Coefficients**
33.391K – 36.391K	$\rho = (\rho_2 + \rho_3 * T)/(1+ \rho_1 * \mathrm{T})$	$\rho_{0=}-0.0343$ $\rho_{1=}1.52593$ $\rho_{2=}-0.13217$
36.391K – 83.391K	$\rho = 1.0/(\rho_0 + \rho_0 * \mathrm{T} + \rho_2 * \mathrm{T})$	$\rho_{0=}-0.05832$ $\rho_{1=}0.00427$ $\rho_{2=}-5.74\mathrm{E}{-}06$

The above Table 3 show the correlations for density of hydrogen, which is obtained against the temperature range of 33.391K-83.391K in the supercritical region.

Table 4 **Correlations Table for specific heat of Hydrogen in supercritical region**

Temperature Range	**Correlation**	**Correlation Coefficients**
33.191 K ≤ T ≤ 34.191 K	$C_p = (C_{p1}+T)/(C_{p0}+C_{p2}*T)$	c_{p0} =0.05121 c_{p1} =0.06239 c_{p2} =0.06239
34.291 K ≤ T ≤ 40.091 K	$C_p = (C_{p1}+T)/(C_{p0}+C_{p2}*T)$	c_{p1} =0.02122 c_{p0} =0.00211 c_{p2} =7.4847E-5

Table 4 show the correlations for specific heat of hydrogen, which is obtained against the temperature range of 33.391K-83.391K in the supercritical region.

Table 5 **Correlations Table for Viscosity of Hydrogen in supercritical region**

Temperature Range	**Correlation**	**Correlation Coefficients**
33.191 K ≤ T ≤ 36.091 K	$\mu = (\mu_1 + \mu_2 * T)/(1+ \mu_0*T)$	$\mu_{0=}$-0.03049 $\mu_{1=}$0.00218 $\mu_{2=}$-6.66E-05
36.191 K ≤ T ≤ 83.191K	$\mu = 1.0/(\mu_0+ \mu_0*T +\mu_2*T)$	$\mu_{0=}$720.1547 $\mu_{1=}$-9.06962 $\mu_{2=}$0.04334

The Table 5 show the correlations for viscosity of hydrogen, which is obtained against the temperature range of 33.391K-83.391K in the supercritical region.

Table 6 Correlations Table for thermal conductivity of Hydrogen in supercritical region

Temperature Range	Correlation	Correlation Coefficients
33.191 K $\leq$ T $\leq$ 38.091K	$\kappa = (1+\kappa_2 T)/(\kappa_0 + \kappa_1 * T)$	$\kappa_{0=}25.46085$ $\kappa_{1=}-0.75723$ $\kappa_{2=}-0.02983$
38.191 K $\leq$ T $\leq$ 38.991 K	$\kappa = 1.0/(\kappa_0 + \kappa_1 * T + \kappa_2 * T\hat{}2)$	$\kappa_{0=}35.66388$ $\kappa_{1=}-0.296$ $\kappa_{2=}7.37E-04$

The Table 6 show the correlations for thermal conductivity of hydrogen, which is obtained against the temperature range of 33.391K-83.391K in the supercritical region.

7.2 DEVIATION OF THERMOPHYSICAL PROPERTIES BEYOND CRITICAL POINT

In Figure 9 to Figure 13 the estimates of the thermophysical properties such as density, specific heat, thermal conductivity and viscosity beyond critical point for Supercritical Hydrogen (SCH) are plotted. Variation of thermophysical properties for a pressure range of 1.312 bar above the critical pressure P_c with an increment of 1 bar is plotted in graph.

7.2.1 DENSITY:

The above graph in Figure 9 is drawn between density and temperature at varying pressure, shows decrease in value of density with the increase in temperature. The decrease in value of density follows a uniform path; there isn't any sudden increase in the value of density. An overview of the density graph shows a decrease in the value of density with the increase in temperature. A sudden change in the density value is observed above the critical temperature T_c

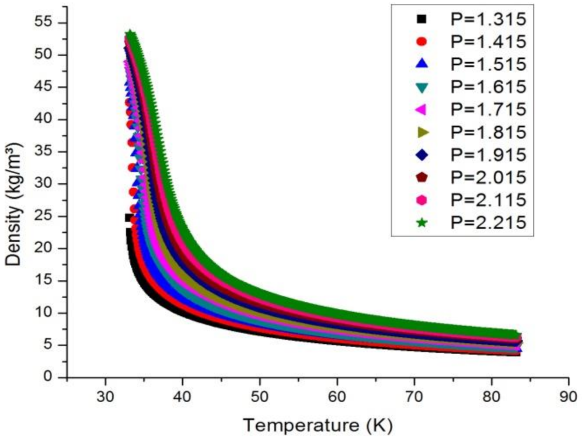


Figure 9 **Density as a function of temperature at different pressure**

7.2.2 SPECIFIC HEAT:

The relation between specific heat and temperature at varying pressure is depicted in Figure10. The pressure lines at different pressures shown in the graph are not identical. The thermophysical properties of SCH as a function of temperature at varying pressure are shown in Figure 10. At constant pressure, Cp value decreases as temperature increases. However, as the pressure increases the corresponding values of specific heat increases. The Cp lines at different pressures shown in Figure 10 are identical with respect to temperature

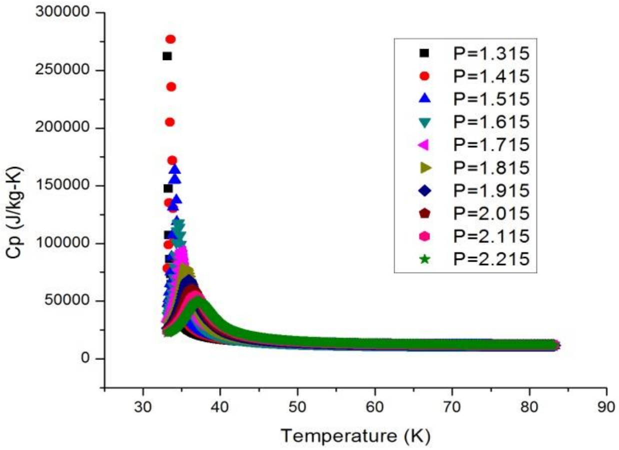


Figure 10 **Specific heat as a function of temperature at different pressures**

7.2.3 THERMAL CONDUCTIVITY:

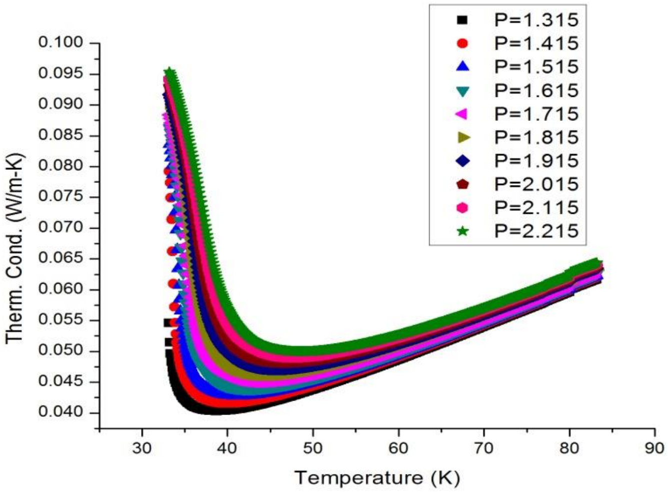


Figure 11 **Thermal conductivity as a function of temperature at different pressures**

Figure 11 shows thermal conductivity as a function of temperature at different pressures. There is a sudden fall in thermal conductivity followed by gradual increase in it with further raise in temperature. There is a sudden fall in thermal conductivity followed by gradual increase in temperature. Figure 11 draws down the conclusion of inferior flow with compact heat absorption with respect to thermal conductivity.

7.2.4 VISCOSITY:

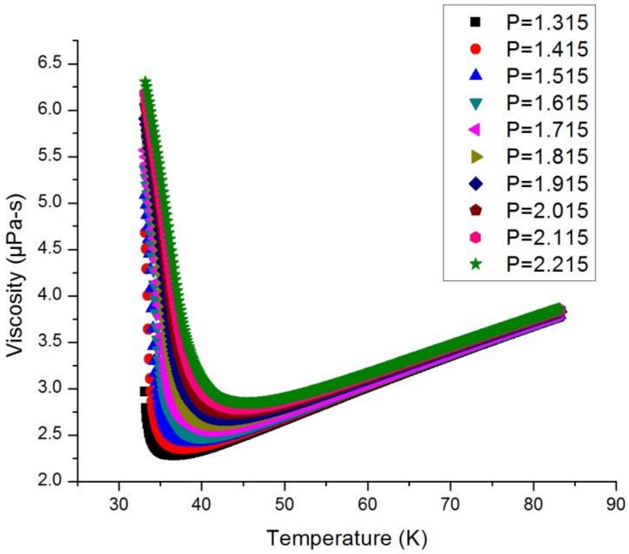


Figure 12 **Viscosity as a function of temperature at different pressures**

Viscosity as a function of temperature at different pressures is depicted in Figure 12. The value of viscosity tends to fall at initial, but gradually increases with increase in temperature. The path carried out by viscosity is non uniform and tends to vary. The variation in the value is fitted using the polynomial and errors are calculated. In the case of viscosity, the value of viscosity tends to fall at initial, however gradually increases with increase in temperature. The paths carried out by viscosity at various pressures are identical with slender variation. That slight variation in the value is fitted and errors are calculated. The plunge in viscosity proves improved flow rate of SCH. Furthermore, the temperature range taken into consideration while plotting the graph is from 33.191K - 83.191K.

7.3 3-D SURFACE PLOTS

3-D plots has been developed by using MATLAB [22] tool, in order to predict the deviation of thermophysical properties of Supercritical Hydrogen (SCH) as a function of pressure and temperature.

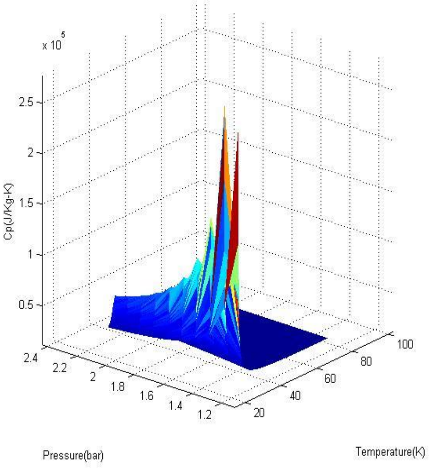
7.3.1 3-D SURFACE PLOT FOR SCH

In the supercritical region Figure 13 shows the deviation of density for SCH as a function of temperature and pressure. The plot shows deviation in property over an extensive range of temperature (33.191K-83.191K) and pressure (1.312bar-2.312bar) in the supercritical regime. At critical pressure the amount at which density drops with reverence to temperature is found to be higher than that of elevated pressures which is depicted in Figure 13. There is not much variation in the density for all pressure ranges at a temperature higher than 42K. The density of SCN tends to increase as pressure increases above critical value, and this rise in density is found to decrease as pressure rises for all temperature ranges.

SPECIFIC HEAT:

As a function of temperature and pressure in the supercritical regime Figure13 shows the deviation of specific heat for SCH. In the supercritical region the peak value is attained at P_C=1.712bar and temperature of about 43.19K which is depicted in Figure13. However, above critical point when pressure increases it can be observed that radical change in the specific heat of SCH has been detected. Figure 13 shows that, at higher temperatures 43K, there is not much deviation in the specific heat values for all pressure ranges.

Figure 13 **3-D Plot of Specific heat as a function of temperature at different pressures**



DENSITY:

Figure 14 shows that in the supercritical regime there is the occurrence of variation in density for SCH as a function of pressure and temperature. The plot shows that in the supercritical region, at P_C=2.112bar and temperature of about 34.19K the peak value is attained. Besides, above critical point as the pressure increases it can be observed that radical change in the specific heat of SCH has been witnessed. Figure 14 depicts that, there is not much variation in the density values for all pressure ranges at higher temperatures 42.19K.

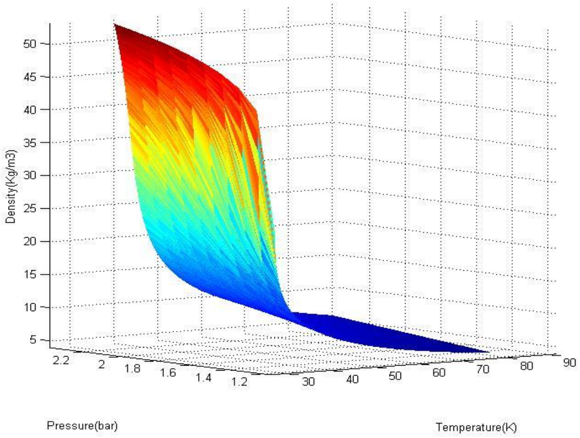


Figure 14 **3-D Plot of Density as a function of temperature at different pressure**

THERMAL CONDUCTIVITY:

Figure 15 shows that in the supercritical regime there is the occurrence of variation in thermal conductivity for SCH as a function of pressure and temperature. The plot shows that in the supercritical region, at P_C=2.212bar and temperature of about 40.19K the peak value is attained. Besides, above critical point as the pressure increases it can be observed that radical change in the thermal conductivity of SCH has been witnessed. Figure 15 depicts that, there is not much variation in the thermal conductivity values for all pressure ranges at higher temperatures 40.19K.

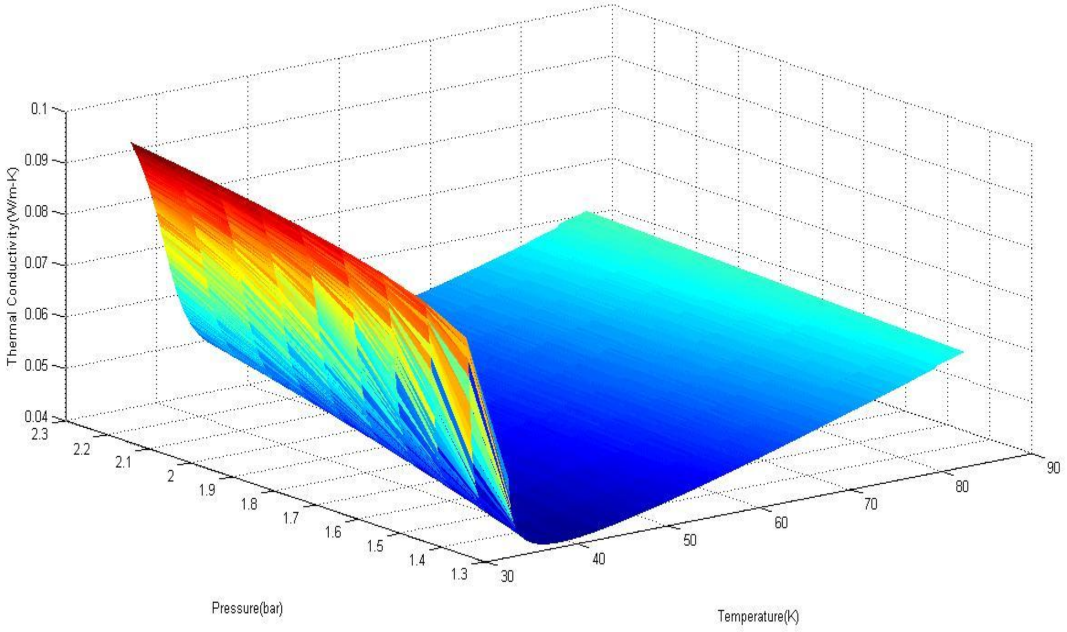


Figure 15 **3-D Plot of Thermal conductivity as a function of temperature at different pressures**

VISCOSITY:

Figure 16 shows that in the supercritical regime there is the occurrence of variation in viscosity for SCH as a function of pressure and temperature. The plot shows that in the supercritical region, at P_C=2.212bar and temperature of about 40.19K the peak value is attained.

Besides, above critical point as the pressure increases it can be observed that radical change in the viscosity of SCH has been witnessed. Figure 16 depicts that, there is not much variation in the thermal conductivity values for all pressure ranges at higher temperatures 40.19K.

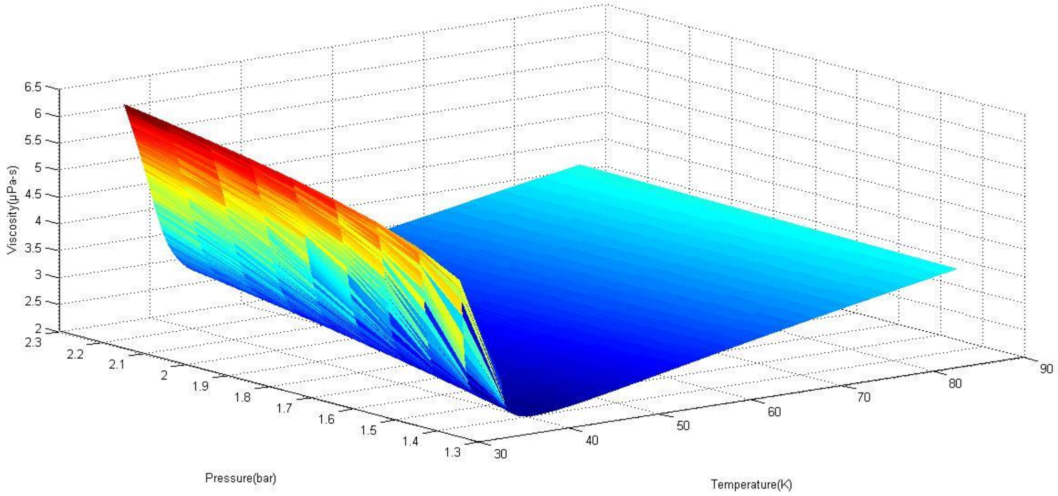


Figure 16 **3-D Plot of Viscosity as a function of temperature at different pressures**

7.4 RESULTS

To establish the accuracy of fitted model, statistical parameters such as Arithmetic Average of the Absolute Values of the Relative Errors (AARE %) and Sum of Absolute of Residual (SAR) have been utilized. Minor values of these strictures refer to reliable correlation. The Arithmetic Average of the Absolute Values of the Relative Errors (AARE %) is defined in Eq. (5).

$$AARE\% = \frac{100}{N}\sum_{i=1}^{499}\left(\left|\frac{X^{\exp} - X^{cal}}{X^{\exp}}\right|\right) \qquad (5)$$

Another such parameter is the Sum of Absolute of Residual (SAR) which is defined in Eq. (6), which put forth the reliability of correlation for more intense data points.

$$SAR = \sum^{499}\left|X^{\exp} - X^{cal}\right| \qquad (6)$$

The Average Percent Relative Error (ARE %) is defined in Eq. (7), which gives a measure of the foregone conclusion of the correlation. A value of zero indicates a random of the measured values around the correlation.

$$ARE\% = \frac{100}{N}\sum_{i=1}^{499}\left(\frac{X^{\exp} - X^{cal}}{X^{\exp}}\right) \tag{7}$$

Figure 5 shows Percent Relative Error (RE %) which is defined in Eq. (8) for each thermophysical properties as a function of temperature and pressure.

$$RE\% = 100 \times \left(\frac{X^{\exp} - X^{cal}}{X^{\exp}}\right) \tag{8}$$

The AARE%, ARE% and SAR values of the correlation developed for SCH in comparison with the NIST values of every thermophysical properties is revealed in Table 7.

Table 7 Statistical value for each thermophysical properties at P_c=1.315Mpa

Properties	AARE%	ARE%	SAR
Density	1.127258224	-0.095453231	51.53836
Viscosity	0.459410202	0.233573648	0.005964
Specific heat	0.690231059	0.00121674	47.71263023
Thermal Conductivity	0.307556957	-0.002299476	0.070829131

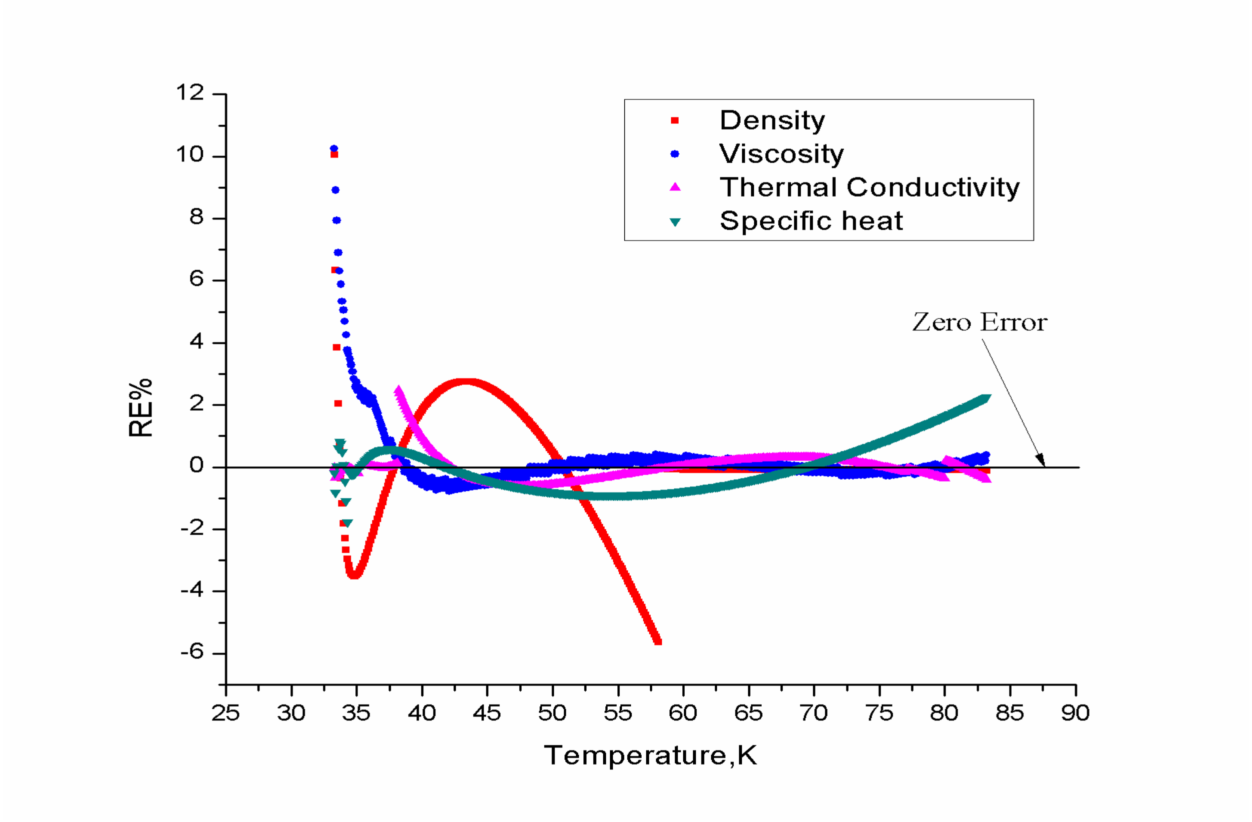


Figure 17 RE% of correlations as function of temperature

The RE% sinks down with gradual increase in temperature, which is shown in **Figure 17**. It is evident that with the decline in value RE%, higher accuracy and precise flow of SCH can be attained in HTS generators

The correlations which are simple to exploit are being proposed in this work, to accurately predict the various thermophysical properties as a function of temperature and pressure. This model was obtained from 500 experimental measurements and is valid in temperature range from 33.191K - 83.191K, and pressures range between 1.315MPa and 2.215MPa. The major boon of using this correlation is that it does not need large number of parameters. The projected correlation has generally resulted in minimum values of RE% in comparison with the NIST web book data.

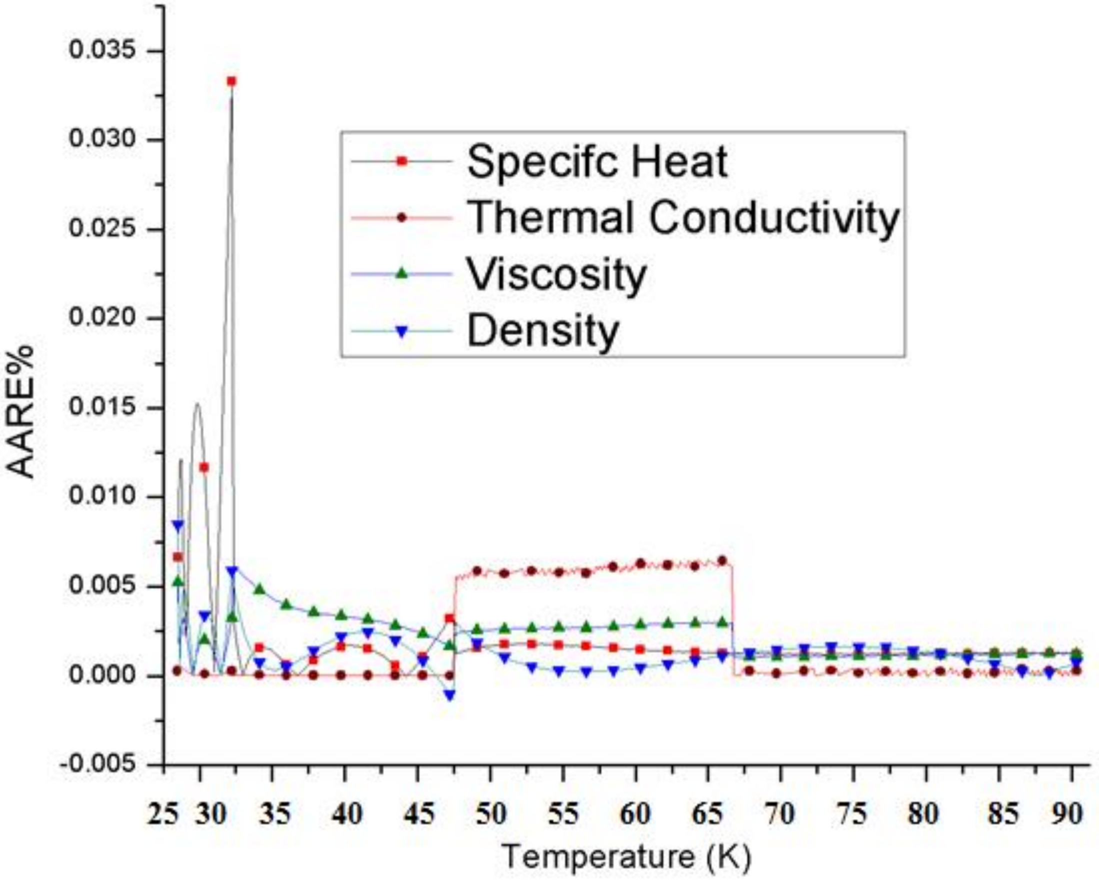
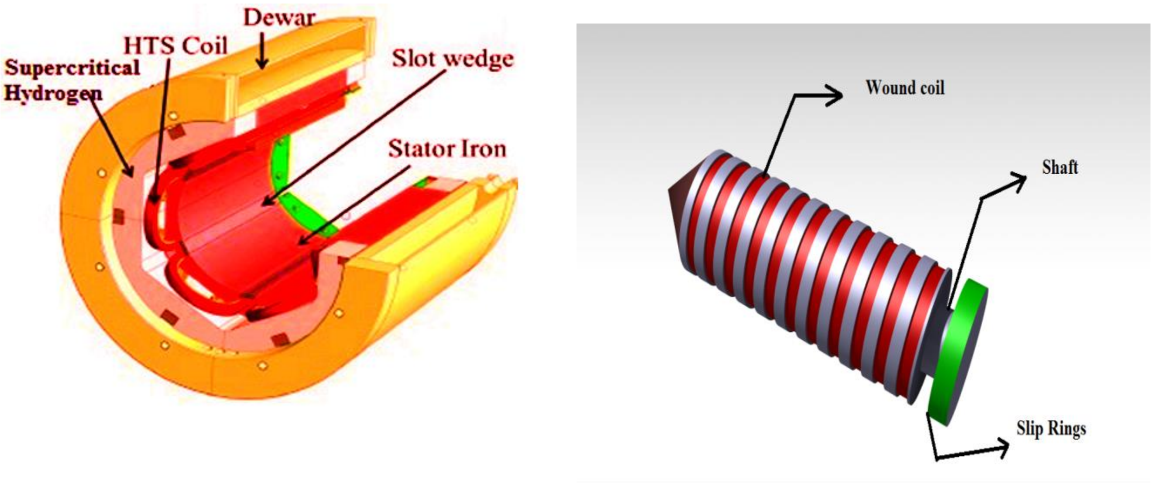


Figure 17(a) AARE% of correlations as function of temperature

The AARE% plunges and then sinks down with gradual increase in temperature, which is shown in **Figure 17(a)**. It is evident that with the decline in value AARE%, higher accuracy and precise flow of SCH can be attained in HTS generators.

7.5 VALIDATION OF DEVELOPED CORRELATION:

Stator is the stationary part of an electrical machine. Henceforth, the stator acts as the field magnet, interacting with the armature to create motion, or it receives its influence from moving field coils on the rotor to act as an armature. An alternator rotor is made up of a HTS wire coil enclosed around an iron core. Steel laminations are used as the magnetic component of the rotor to aid inscribing conductor slots to specific sizes and shapes. A magnetic field is created around the core when currents travel through the wire coil, which is referred to as field current. The power level of the magnetic field is controlled by the field current strength.



(a) Stator component of HTS Generator (b) Rotor component of HTS
Generator

Figure.18 Central Components of HTS Generator using ANSYS Workbench14.0

Table8 and Table9 depict the design parameters with which HTS generator has been designed for the analysis flow of SCH with proposed correlations. Bi-2223 and the YBCO-344 are the two types of high strength commercial HTS tapes manufactured by American Superconductor Corp., to wound around the HTS excitation coils in the rotor of the generator.

Table (8),(9) Design aspects of the model generator [18],p_c=1.315mpa

DESIGN PARAMETERS OF THE MODEL GENERATOR			
Rated output power (kW)	**100**	Pair of rotor poles, *p*	3
Phases	**3**	Stator outer diameter (mm)	740
Rated output voltage (V)	**690**	Stator inner diameter (mm)	450
Rated output current/phase (A)	**84**	Stator Length (mm)	660

Rated output frequency (Hz)	**50**	Air gap width (mm)	17
Rated generator frequency, *f*(Hz)	**10**	Rotor outer diameter (mm)	416
Rated rotation speed, *n*(rpm)	**200**	Excitation coil width (mm)	156
Rated excitation current (A)	**50**	Excitation coil height (mm)	52
Air gap field (T)	**0.91**	Excitation coil length (mm)	622
Rotor working temperature (K)	**77**	Winding width (mm)	36
Rotor current density (A/mm^2)	**8.5**	Pancake coils per pole	8
Active armature length *l (mm)*	**500**	Turns per pancake coil	40

Parameters and parameters of the HTS Tapes		
Types of HTS tapes	YBCO – 344	Bi -2223
Thickness (mm)	0.36 – 0.44	0.255 – 0.285
Width (mm)	4.24 – 4.45	4.2 – 4.4
Min. RT bend diameter (mm)	35	38
Max. rated tensile stress (RT)	200 MPa	200 Mpa
Max. rated wire tension (RT)	20 Kg	21 Kg
Max. rated tensile strain (77K)	0.3%	0.4%
I_{c0} (self field, 77 K)	~100A	~145A
I_c/I_{c0}at 0.3 T prep. Field (77K)	~0.6	~0.1
I_c/I_{c0}at 0.3 T para. Field (77K)	~0.65	~0.6
I_c/I_{c0}at 0.5 T prep. Field (65K)	~0.9	-
I_c/I_{c0}at 0.5 T para. Field (65K)	~1.1	-

7.5 STATISTICAL ANALYSIS OF CORRELATIONS:

The cross-sectional view of the stator showing magnetic field and flux distribution is depicted above. The result obtained here is for the flow of super critical helium at 160 m/sec, around HTS generator

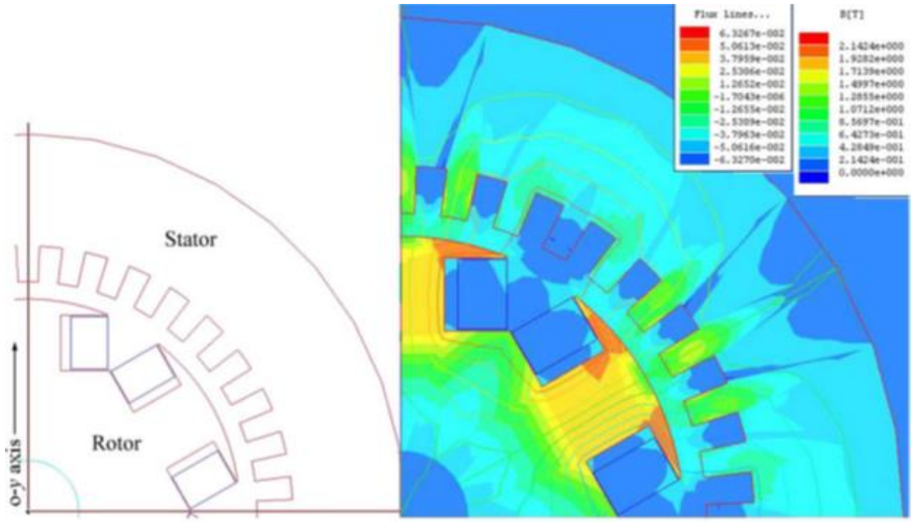


Figure. 19. Cross section view (a) numerical simulation result of the magnetic field and flux distribution at 50 A working current (b) of the model [18]

The same result when compared with that of the super critical hydrogen shows improved flow rate of coolant and high heat absorbing capacity in the HTS generator, with the advent of the proposed correlation.

$\kappa = (1+\kappa_2 T)/(\kappa_0 + \kappa_1 * T)$

…. (9) Thermal Conductivity

$C_p = (C_{p1} + T)/ (C_{p0} + C_{p2} * T)$

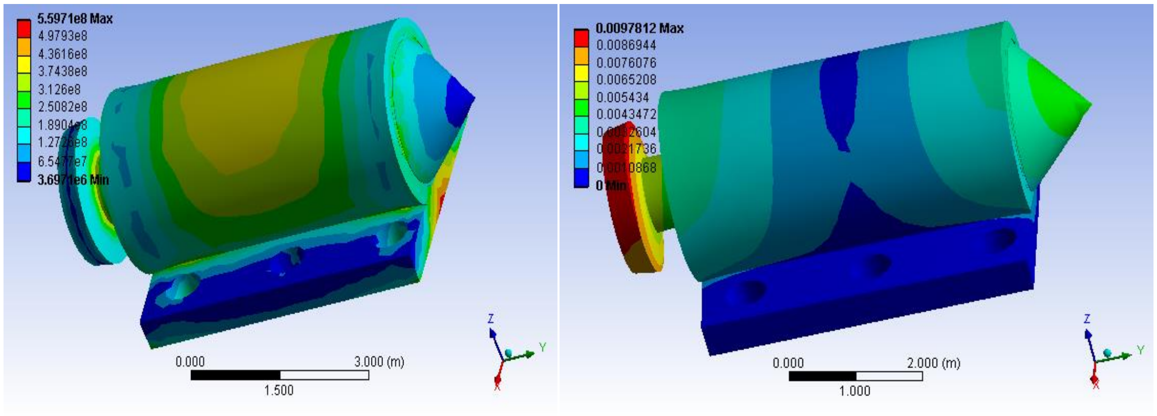
…. (10) Specific Heat

$\rho = (\rho_2 + \rho_3 * T)/(1 + \rho_1 * T)$

…. (11) Density

$\mu = (\mu_1 + \mu_2 * T)/(1 + \mu_0 * T)$

…. (12) Viscosity



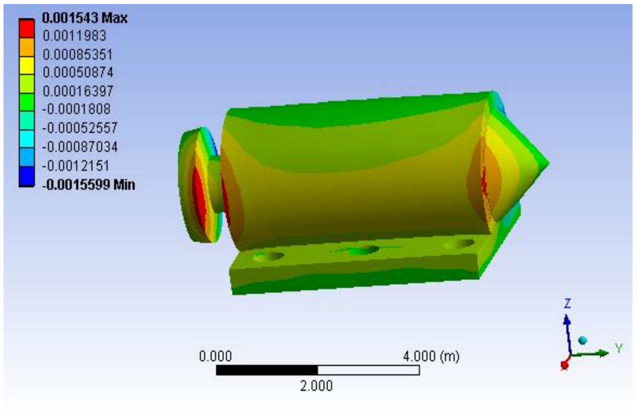


Figure.20 Comparison of flux density between supercritical Helium and Hydrogen

The prime reason for comparison of supercritical hydrogen with supercritical helium is that, the present application of SC He on superconducting generators. The above comparison between the existing supercritical helium and proposed supercritical hydrogen as coolant in HTS generator shows the high thermal conductivity and low density of SCH. The comprehensive analysis of HTS generator with supply of SCH based on the developed correlation shows that the density with which the SCH flows is comparatively less and detailed comparison is as follows.

Thermophysical Properties at T_c	Supercritical Helium	Supercritical Hydrogen
Density (kg/m^3)	125.42	0.99195
Specific Heat (kJ/kg-K)	5.1608	10.814
Therm. Cond. (mW/m-K)	18.651	27.247
Viscosity (µPa-s)	3.1808	1.7262

Table 10 Results of thermophysical values of SCH and SC He

The above table shows the values obtained with the application of SCH and SC He on HTS generator with proposed correlation. The thermophysical property values of SCH obtained are more effective in comparison.

Simulation is done with the obtained correlation with the application of supercritical hydrogen values at 33.19k and 1.312bar using ANSYS workbench 14.0 [25]. It is being observed that the magnetic flux density and distribution of flux is way too uniform when SCH is supplied. The graphical representation shows high heat distribution in super critical hydrogen than in supercritical helium. Moreover, the experimental analysis with practical setup may yield slightly differing values as compared to simulated values.

In the supercritical region, it is difficult to explain whether the fluid is in gas or liquid, such that the fluid performs as a homogeneous mixture. Therefore, on the basis of thermophysical (conveyance and thermodynamic) properties such as thermal conductivity, viscosity, density and specific heat, the results are concluded with respect to temperature and pressure. The results are found to be indenture with NIST REFPROP data [7].

8.1 Density

From Figure 9, it can be concluded that the density of SCH tends to decrease as temperature increases at any precise pressure. Density is getting reduced due to the kinetic attraction between molecules as the pressure and temperature increases, which leads to severe decrease in the intermolecular forces of attraction at the critical point of SCH. Besides, density above critical point i.e. at Pc=1.312bar and Tc=33.19K is found to be increasing gradually with constant curve.

8.2 Specific heat

From Figure 10, it can be concluded that, at critical temperature (Tc=33.19K) and critical pressure (Pc=1.312bar) specific heat of SCH increased drastically and then plunges thereafter. However, it can be concluded from Figure 10 that, there is a drastic drop in specific heat of SCH just above the 0.1K this is due to that, the energy which stored in different forms. The increase in the rate of heat transfer is due to the stored energy is being observed. Due to the thermal instability between the bonds the sudden drop may be observed.

8.3 Thermal conductivity

Figure 11 shows thermal conductivity as a function of temperature and pressure at (Tc=33.19K) and (Pc=1.312bar). There is a sudden fall in thermal conductivity followed by gradual increase in it with further raise in temperature. There is a sudden fall in thermal conductivity followed by gradual increase in temperature. Due to the thermal excitation the various energy modes gets activated and strong molecular interactions can be observed. Figure 11 draws down the conclusion of inferior flow with compact heat absorption with respect to thermal conductivity.

8.4 Viscosity

From Figure 12, it can be resolved that, the variation in viscosity is found to be drastic and it will tend to decrease as the temperature increases. Since, the kinetic energy of the molecules is getting increased and thus the viscosity will tend to decrease. The plunge in viscosity proves improved flow rate of SCH.

8.5 Implication of developed correlation on HTS Generator:

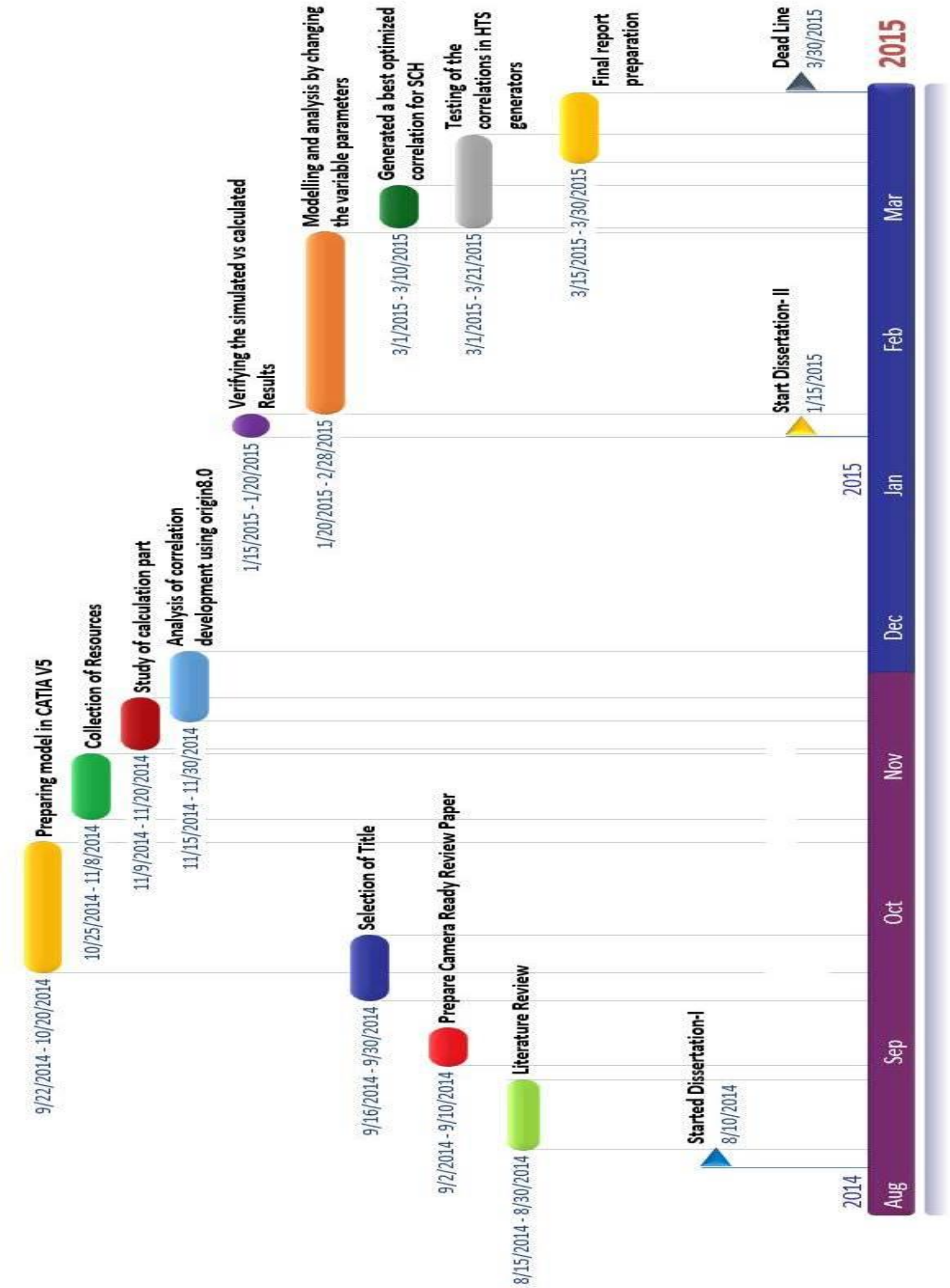
Simulation is done with the obtained correlation with the application of supercritical hydrogen values at 33.19k and 1.312bar using ANSYS workbench 14.0 [25]. It is being observed that the magnetic flux density and distribution of flux is way too uniform when SCH is supplied. The graphical representation shows high heat distribution in super critical hydrogen than in supercritical helium. Moreover, the experimental analysis with practical setup may yield slightly differing values as compared to simulated values.

The development of High Temperature Superconducting (HTS) generator with higher current generation capacity is expected in the near future operating at critical temperatures (>33K). Hence, Supercritical Hydrogen (SCH) plays a vital role in cooling such superconductors and to maintain the critical temperature of Superconductor Generator.

In order to level head High Temperature Superconducting (HTS) generator a cryogenic coolant is required since it is void of evaporation. And moreover it yields complete absorption of heat. Therefore, there indulges temperature dependent thermodynamic and transport properties. The present work may be helpful in foreseeing thermohydraulic performance on High Temperature Superconducting (HTS) generator by using Supercritical Hydrogen (SCH) as a coolant.

However, in order to simplify and reduce the number of correlation coefficients a single correlation applicable to wide temperature ranges may be endeavored in future.

9.1 TIMELINE OF THE WORK



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APPENDIX

Temperature	Pressure	Density	Cp	Therm. Cond.	Viscosity
(K)	(bar)	(kg/m³)	(kJ/kg-K)	(W/m-K)	(μPa-s)
33.191	1.3120	0.99191	10.814	0.027247	1.7263
33.291	1.3120	0.98866	10.810	0.027320	1.7311
33.391	1.3120	0.98543	10.806	0.027393	1.7359
33.491	1.3120	0.98222	10.802	0.027466	1.7407
33.591	1.3120	0.97904	10.798	0.027539	1.7455
33.691	1.3120	0.97588	10.794	0.027611	1.7503
33.791	1.3120	0.97273	10.791	0.027684	1.7551
33.891	1.3120	0.96961	10.787	0.027756	1.7598
33.991	1.3120	0.96651	10.783	0.027829	1.7646
34.091	1.3120	0.96343	10.780	0.027901	1.7694
34.191	1.3120	0.96038	10.776	0.027973	1.7742
34.291	1.3120	0.95734	10.773	0.028045	1.7789
34.391	1.3120	0.95432	10.769	0.028117	1.7837
34.491	1.3120	0.95132	10.766	0.028189	1.7885
34.591	1.3120	0.94834	10.762	0.028261	1.7932
34.691	1.3120	0.94539	10.759	0.028333	1.7980
34.791	1.3120	0.94245	10.756	0.028405	1.8027
34.891	1.3120	0.93953	10.752	0.028476	1.8075
34.991	1.3120	0.93662	10.749	0.028548	1.8122
35.091	1.3120	0.93374	10.746	0.028619	1.8169
35.191	1.3120	0.93088	10.743	0.028690	1.8217
35.291	1.3120	0.92803	10.740	0.028762	1.8264
35.391	1.3120	0.92521	10.737	0.028833	1.8311
35.491	1.3120	0.92240	10.734	0.028904	1.8358
35.591	1.3120	0.91961	10.731	0.028975	1.8406

35.691	1.3120	0.91683	10.728	0.029046	1.8453
35.791	1.3120	0.91408	10.725	0.029116	1.8500
35.891	1.3120	0.91134	10.722	0.029187	1.8547
35.991	1.3120	0.90862	10.719	0.029258	1.8594
36.091	1.3120	0.90591	10.716	0.029328	1.8641
36.191	1.3120	0.90322	10.714	0.029399	1.8688
36.291	1.3120	0.90055	10.711	0.029469	1.8735
36.391	1.3120	0.89790	10.708	0.029540	1.8781
36.491	1.3120	0.89526	10.706	0.029610	1.8828
36.591	1.3120	0.89264	10.703	0.029680	1.8875
36.691	1.3120	0.89003	10.700	0.029750	1.8922
36.791	1.3120	0.88744	10.698	0.029820	1.8968
36.891	1.3120	0.88487	10.695	0.029890	1.9015
36.991	1.3120	0.88231	10.693	0.029960	1.9062
37.091	1.3120	0.87976	10.690	0.030029	1.9108
37.191	1.3120	0.87723	10.688	0.030099	1.9155
37.291	1.3120	0.87472	10.685	0.030169	1.9201
37.391	1.3120	0.87222	10.683	0.030238	1.9247
37.491	1.3120	0.86974	10.681	0.030307	1.9294
37.591	1.3120	0.86727	10.678	0.030377	1.9340
37.691	1.3120	0.86482	10.676	0.030446	1.9386
37.791	1.3120	0.86238	10.674	0.030515	1.9433
37.891	1.3120	0.85995	10.671	0.030584	1.9479
37.991	1.3120	0.85754	10.669	0.030653	1.9525
38.091	1.3120	0.85514	10.667	0.030722	1.9571
38.191	1.3120	0.85276	10.665	0.030791	1.9617
38.291	1.3120	0.85039	10.663	0.030860	1.9663
38.391	1.3120	0.84803	10.661	0.030929	1.9709
38.491	1.3120	0.84569	10.658	0.030997	1.9755
38.591	1.3120	0.84336	10.656	0.031066	1.9801

38.691	1.3120	0.84105	10.654	0.031134	1.9847
38.791	1.3120	0.83874	10.652	0.031203	1.9893
38.891	1.3120	0.83645	10.650	0.031271	1.9939
38.991	1.3120	0.83418	10.648	0.031339	1.9984
39.091	1.3120	0.83191	10.646	0.031407	2.0030
39.191	1.3120	0.82966	10.644	0.031475	2.0076
39.291	1.3120	0.82743	10.642	0.031543	2.0121
39.391	1.3120	0.82520	10.640	0.031611	2.0167
39.491	1.3120	0.82299	10.639	0.031679	2.0212
39.591	1.3120	0.82079	10.637	0.031747	2.0258
39.691	1.3120	0.81860	10.635	0.031815	2.0303
39.791	1.3120	0.81642	10.633	0.031883	2.0349
39.891	1.3120	0.81426	10.631	0.031950	2.0394
39.991	1.3120	0.81210	10.629	0.032018	2.0439
40.091	1.3120	0.80996	10.628	0.032085	2.0485
40.191	1.3120	0.80783	10.626	0.032153	2.0530
40.291	1.3120	0.80571	10.624	0.032220	2.0575
40.391	1.3120	0.80361	10.623	0.032287	2.0620
40.491	1.3120	0.80151	10.621	0.032354	2.0665
40.591	1.3120	0.79943	10.619	0.032422	2.0710
40.691	1.3120	0.79736	10.618	0.032489	2.0755
40.791	1.3120	0.79529	10.616	0.032556	2.0800
40.891	1.3120	0.79324	10.614	0.032623	2.0845
40.991	1.3120	0.79120	10.613	0.032689	2.0890
41.091	1.3120	0.78918	10.611	0.032756	2.0935
41.191	1.3120	0.78716	10.610	0.032823	2.0980
41.291	1.3120	0.78515	10.608	0.032890	2.1024
41.391	1.3120	0.78315	10.606	0.032956	2.1069
41.491	1.3120	0.78117	10.605	0.033023	2.1114
41.591	1.3120	0.77919	10.603	0.033089	2.1158

41.691	1.3120	0.77723	10.602	0.033156	2.1203
41.791	1.3120	0.77527	10.600	0.033222	2.1247
41.891	1.3120	0.77332	10.599	0.033288	2.1292
41.991	1.3120	0.77139	10.598	0.033355	2.1336
42.091	1.3120	0.76946	10.596	0.033421	2.1381
42.191	1.3120	0.76755	10.595	0.033487	2.1425
42.291	1.3120	0.76564	10.593	0.033553	2.1469
42.391	1.3120	0.76375	10.592	0.033619	2.1514
42.491	1.3120	0.76186	10.591	0.033685	2.1558
42.591	1.3120	0.75998	10.589	0.033751	2.1602
42.691	1.3120	0.75812	10.588	0.033817	2.1646
42.791	1.3120	0.75626	10.587	0.033883	2.1690
42.891	1.3120	0.75441	10.585	0.033948	2.1734
42.991	1.3120	0.75257	10.584	0.034014	2.1778
43.091	1.3120	0.75074	10.583	0.034080	2.1822
43.191	1.3120	0.74892	10.581	0.034145	2.1866
43.291	1.3120	0.74711	10.580	0.034211	2.1910
43.391	1.3120	0.74531	10.579	0.034276	2.1954
43.491	1.3120	0.74352	10.578	0.034341	2.1998
43.591	1.3120	0.74173	10.577	0.034407	2.2041
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43.791	1.3120	0.73819	10.574	0.034537	2.2129
43.891	1.3120	0.73643	10.573	0.034602	2.2173
43.991	1.3120	0.73468	10.572	0.034668	2.2216
44.091	1.3120	0.73294	10.571	0.034733	2.2260
44.191	1.3120	0.73121	10.570	0.034798	2.2303
44.291	1.3120	0.72948	10.568	0.034863	2.2347
44.391	1.3120	0.72777	10.567	0.034928	2.2390
44.491	1.3120	0.72606	10.566	0.034992	2.2433
44.591	1.3120	0.72436	10.565	0.035057	2.2477

44.691	1.3120	0.72267	10.564	0.035122	2.2520
44.791	1.3120	0.72098	10.563	0.035187	2.2563
44.891	1.3120	0.71931	10.562	0.035251	2.2606
44.991	1.3120	0.71764	10.561	0.035316	2.2650
45.091	1.3120	0.71598	10.560	0.035381	2.2693
45.191	1.3120	0.71433	10.559	0.035445	2.2736
45.291	1.3120	0.71269	10.558	0.035510	2.2779
45.391	1.3120	0.71105	10.557	0.035574	2.2822
45.491	1.3120	0.70942	10.556	0.035639	2.2865
45.591	1.3120	0.70780	10.555	0.035703	2.2908
45.691	1.3120	0.70619	10.554	0.035767	2.2951
45.791	1.3120	0.70458	10.553	0.035831	2.2993
45.891	1.3120	0.70299	10.552	0.035896	2.3036
45.991	1.3120	0.70139	10.551	0.035960	2.3079
46.091	1.3120	0.69981	10.550	0.036024	2.3122
46.191	1.3120	0.69824	10.549	0.036088	2.3164
46.291	1.3120	0.69667	10.548	0.036152	2.3207
46.391	1.3120	0.69511	10.548	0.036216	2.3250
46.491	1.3120	0.69355	10.547	0.036280	2.3292
46.591	1.3120	0.69200	10.546	0.036344	2.3335
46.691	1.3120	0.69046	10.545	0.036408	2.3377
46.791	1.3120	0.68893	10.544	0.036472	2.3419
46.891	1.3120	0.68741	10.543	0.036536	2.3462
46.991	1.3120	0.68589	10.543	0.036599	2.3504
47.091	1.3120	0.68437	10.542	0.036663	2.3546
47.191	1.3120	0.68287	10.541	0.036727	2.3589
47.291	1.3120	0.68137	10.540	0.036791	2.3631
47.391	1.3120	0.67988	10.539	0.036854	2.3673
47.491	1.3120	0.67839	10.539	0.036918	2.3715
47.591	1.3120	0.67691	10.538	0.036981	2.3757

47.691	1.3120	0.67544	10.537	0.037045	2.3799
47.791	1.3120	0.67398	10.536	0.037108	2.3841
47.891	1.3120	0.67252	10.536	0.037172	2.3883
47.991	1.3120	0.67107	10.535	0.037235	2.3925
48.091	1.3120	0.66962	10.534	0.037298	2.3967
48.191	1.3120	0.66818	10.533	0.037362	2.4009
48.291	1.3120	0.66675	10.533	0.037425	2.4051
48.391	1.3120	0.66532	10.532	0.037488	2.4093
48.491	1.3120	0.66390	10.531	0.037552	2.4134
48.591	1.3120	0.66248	10.531	0.037615	2.4176
48.691	1.3120	0.66108	10.530	0.037678	2.4218
48.791	1.3120	0.65967	10.530	0.037741	2.4259
48.891	1.3120	0.65828	10.529	0.037804	2.4301
48.991	1.3120	0.65689	10.528	0.037867	2.4342
49.091	1.3120	0.65550	10.528	0.037930	2.4384
49.191	1.3120	0.65412	10.527	0.037993	2.4425
49.291	1.3120	0.65275	10.526	0.038056	2.4467
49.391	1.3120	0.65139	10.526	0.038119	2.4508
49.491	1.3120	0.65002	10.525	0.038182	2.4549
49.591	1.3120	0.64867	10.525	0.038245	2.4591
49.691	1.3120	0.64732	10.524	0.038308	2.4632
49.791	1.3120	0.64598	10.524	0.038371	2.4673
49.891	1.3120	0.64464	10.523	0.038434	2.4714
49.991	1.3120	0.64331	10.523	0.038496	2.4756
50.091	1.3120	0.64198	10.522	0.038559	2.4797
50.191	1.3120	0.64066	10.522	0.038622	2.4838
50.291	1.3120	0.63935	10.521	0.038685	2.4879
50.391	1.3120	0.63804	10.521	0.038747	2.4920
50.491	1.3120	0.63673	10.520	0.038810	2.4961
50.591	1.3120	0.63543	10.520	0.038873	2.5002

50.691	1.3120	0.63414	10.519	0.038935	2.5042
50.791	1.3120	0.63285	10.519	0.038998	2.5083
50.891	1.3120	0.63157	10.518	0.039060	2.5124
50.991	1.3120	0.63029	10.518	0.039123	2.5165
51.091	1.3120	0.62902	10.517	0.039185	2.5206
51.191	1.3120	0.62775	10.517	0.039248	2.5246
51.291	1.3120	0.62649	10.517	0.039310	2.5287
51.391	1.3120	0.62523	10.516	0.039373	2.5328
51.491	1.3120	0.62398	10.516	0.039435	2.5368
51.591	1.3120	0.62274	10.515	0.039497	2.5409
51.691	1.3120	0.62149	10.515	0.039560	2.5449
51.791	1.3120	0.62026	10.515	0.039622	2.5490
51.891	1.3120	0.61903	10.514	0.039684	2.5530
51.991	1.3120	0.61780	10.514	0.039747	2.5570
52.091	1.3120	0.61658	10.514	0.039809	2.5611
52.191	1.3120	0.61536	10.513	0.039871	2.5651
52.291	1.3120	0.61415	10.513	0.039933	2.5691
52.391	1.3120	0.61294	10.513	0.039996	2.5732
52.491	1.3120	0.61174	10.512	0.040058	2.5772
52.591	1.3120	0.61055	10.512	0.040120	2.5812
52.691	1.3120	0.60935	10.512	0.040182	2.5852
52.791	1.3120	0.60817	10.512	0.040244	2.5892
52.891	1.3120	0.60698	10.511	0.040306	2.5932
52.991	1.3120	0.60581	10.511	0.040369	2.5972
53.091	1.3120	0.60463	10.511	0.040431	2.6012
53.191	1.3120	0.60346	10.511	0.040493	2.6052
53.291	1.3120	0.60230	10.510	0.040555	2.6092
53.391	1.3120	0.60114	10.510	0.040617	2.6132
53.491	1.3120	0.59998	10.510	0.040679	2.6172
53.591	1.3120	0.59883	10.510	0.040741	2.6211

53.691	1.3120	0.59769	10.510	0.040803	2.6251
53.791	1.3120	0.59655	10.509	0.040865	2.6291
53.891	1.3120	0.59541	10.509	0.040927	2.6331
53.991	1.3120	0.59428	10.509	0.040989	2.6370
54.091	1.3120	0.59315	10.509	0.041051	2.6410
54.191	1.3120	0.59202	10.509	0.041112	2.6450
54.291	1.3120	0.59090	10.509	0.041174	2.6489
54.391	1.3120	0.58979	10.509	0.041236	2.6529
54.491	1.3120	0.58868	10.508	0.041298	2.6568
54.591	1.3120	0.58757	10.508	0.041360	2.6607
54.691	1.3120	0.58647	10.508	0.041422	2.6647
54.791	1.3120	0.58537	10.508	0.041484	2.6686
54.891	1.3120	0.58427	10.508	0.041545	2.6726
54.991	1.3120	0.58318	10.508	0.041607	2.6765
55.091	1.3120	0.58210	10.508	0.041669	2.6804
55.191	1.3120	0.58102	10.508	0.041731	2.6843
55.291	1.3120	0.57994	10.508	0.041793	2.6883
55.391	1.3120	0.57887	10.508	0.041854	2.6922
55.491	1.3120	0.57780	10.508	0.041916	2.6961
55.591	1.3120	0.57673	10.508	0.041978	2.7000
55.691	1.3120	0.57567	10.508	0.042039	2.7039
55.791	1.3120	0.57461	10.508	0.042101	2.7078
55.891	1.3120	0.57356	10.508	0.042163	2.7117
55.991	1.3120	0.57251	10.508	0.042225	2.7156
56.091	1.3120	0.57146	10.508	0.042286	2.7195
56.191	1.3120	0.57042	10.508	0.042348	2.7234
56.291	1.3120	0.56938	10.508	0.042410	2.7273
56.391	1.3120	0.56835	10.508	0.042471	2.7312
56.491	1.3120	0.56732	10.508	0.042533	2.7350
56.591	1.3120	0.56629	10.508	0.042594	2.7389

56.691	1.3120	0.56527	10.508	0.042656	2.7428
56.791	1.3120	0.56425	10.508	0.042718	2.7466
56.891	1.3120	0.56323	10.508	0.042779	2.7505
56.991	1.3120	0.56222	10.508	0.042841	2.7544
57.091	1.3120	0.56121	10.509	0.042902	2.7582
57.191	1.3120	0.56021	10.509	0.042964	2.7621
57.291	1.3120	0.55921	10.509	0.043026	2.7659
57.391	1.3120	0.55821	10.509	0.043087	2.7698
57.491	1.3120	0.55722	10.509	0.043149	2.7736
57.591	1.3120	0.55623	10.509	0.043210	2.7775
57.691	1.3120	0.55524	10.509	0.043272	2.7813
57.791	1.3120	0.55426	10.510	0.043333	2.7852
57.891	1.3120	0.55328	10.510	0.043395	2.7890
57.991	1.3120	0.55230	10.510	0.043456	2.7928
58.091	1.3120	0.55133	10.510	0.043518	2.7966
58.191	1.3120	0.55036	10.510	0.043579	2.8005
58.291	1.3120	0.54940	10.511	0.043641	2.8043
58.391	1.3120	0.54843	10.511	0.043702	2.8081
58.491	1.3120	0.54748	10.511	0.043764	2.8119
58.591	1.3120	0.54652	10.511	0.043826	2.8157
58.691	1.3120	0.54557	10.512	0.043887	2.8195
58.791	1.3120	0.54462	10.512	0.043948	2.8233
58.891	1.3120	0.54368	10.512	0.044010	2.8271
58.991	1.3120	0.54273	10.512	0.044071	2.8309
59.091	1.3120	0.54180	10.513	0.044133	2.8347
59.191	1.3120	0.54086	10.513	0.044194	2.8385
59.291	1.3120	0.53993	10.513	0.044256	2.8423
59.391	1.3120	0.53900	10.514	0.044317	2.8461
59.491	1.3120	0.53807	10.514	0.044379	2.8499
59.591	1.3120	0.53715	10.514	0.044440	2.8536

59.691	1.3120	0.53623	10.515	0.044502	2.8574
59.791	1.3120	0.53532	10.515	0.044563	2.8612
59.891	1.3120	0.53441	10.515	0.044625	2.8650
59.991	1.3120	0.53350	10.516	0.044686	2.8687
60.091	1.3120	0.53259	10.516	0.044748	2.8725
60.191	1.3120	0.53169	10.516	0.044809	2.8762
60.291	1.3120	0.53079	10.517	0.044870	2.8800
60.391	1.3120	0.52989	10.517	0.044932	2.8838
60.491	1.3120	0.52900	10.518	0.044993	2.8875
60.591	1.3120	0.52811	10.518	0.045055	2.8913
60.691	1.3120	0.52722	10.519	0.045116	2.8950
60.791	1.3120	0.52633	10.519	0.045178	2.8987
60.891	1.3120	0.52545	10.519	0.045239	2.9025
60.991	1.3120	0.52457	10.520	0.045301	2.9062
61.091	1.3120	0.52370	10.520	0.045362	2.9099
61.191	1.3120	0.52282	10.521	0.045424	2.9137
61.291	1.3120	0.52195	10.521	0.045485	2.9174
61.391	1.3120	0.52109	10.522	0.045546	2.9211
61.491	1.3120	0.52022	10.522	0.045608	2.9248
61.591	1.3120	0.51936	10.523	0.045669	2.9286
61.691	1.3120	0.51850	10.523	0.045731	2.9323
61.791	1.3120	0.51765	10.524	0.045792	2.9360
61.891	1.3120	0.51680	10.524	0.045854	2.9397
61.991	1.3120	0.51595	10.525	0.045915	2.9434
62.091	1.3120	0.51510	10.526	0.045977	2.9471
62.191	1.3120	0.51426	10.526	0.046038	2.9508
62.291	1.3120	0.51341	10.527	0.046100	2.9545
62.391	1.3120	0.51258	10.527	0.046161	2.9582
62.491	1.3120	0.51174	10.528	0.046222	2.9619
62.591	1.3120	0.51091	10.528	0.046284	2.9656

62.691	1.3120	0.51008	10.529	0.046345	2.9693
62.791	1.3120	0.50925	10.530	0.046407	2.9729
62.891	1.3120	0.50842	10.530	0.046468	2.9766
62.991	1.3120	0.50760	10.531	0.046530	2.9803
63.091	1.3120	0.50678	10.532	0.046591	2.9840
63.191	1.3120	0.50597	10.532	0.046653	2.9876
63.291	1.3120	0.50515	10.533	0.046714	2.9913
63.391	1.3120	0.50434	10.534	0.046776	2.9950
63.491	1.3120	0.50353	10.534	0.046837	2.9986
63.591	1.3120	0.50273	10.535	0.046899	3.0023
63.691	1.3120	0.50192	10.536	0.046960	3.0059
63.791	1.3120	0.50112	10.536	0.047022	3.0096
63.891	1.3120	0.50032	10.537	0.047083	3.0132
63.991	1.3120	0.49953	10.538	0.047145	3.0169
64.091	1.3120	0.49874	10.538	0.047206	3.0205
64.191	1.3120	0.49795	10.539	0.047268	3.0242
64.291	1.3120	0.49716	10.540	0.047329	3.0278
64.391	1.3120	0.49637	10.541	0.047391	3.0315
64.491	1.3120	0.49559	10.541	0.047452	3.0351
64.591	1.3120	0.49481	10.542	0.047514	3.0387
64.691	1.3120	0.49403	10.543	0.047575	3.0423
64.791	1.3120	0.49325	10.544	0.047637	3.0460
64.891	1.3120	0.49248	10.545	0.047699	3.0496
64.991	1.3120	0.49171	10.545	0.047760	3.0532
65.091	1.3120	0.49094	10.546	0.047822	3.0568
65.191	1.3120	0.49018	10.547	0.047883	3.0604
65.291	1.3120	0.48941	10.548	0.047945	3.0641
65.391	1.3120	0.48865	10.549	0.048006	3.0677
65.491	1.3120	0.48789	10.550	0.048068	3.0713
65.591	1.3120	0.48714	10.550	0.048130	3.0749

65.691	1.3120	0.48638	10.551	0.048191	3.0785
65.791	1.3120	0.48563	10.552	0.048253	3.0821
65.891	1.3120	0.48488	10.553	0.048314	3.0857
65.991	1.3120	0.48414	10.554	0.048376	3.0893
66.091	1.3120	0.48339	10.555	0.048438	3.0929
66.191	1.3120	0.48265	10.556	0.048499	3.0964
66.291	1.3120	0.48191	10.557	0.048561	3.1000
66.391	1.3120	0.48117	10.558	0.048623	3.1036
66.491	1.3120	0.48044	10.558	0.048684	3.1072
66.591	1.3120	0.47971	10.559	0.048746	3.1108
66.691	1.3120	0.47897	10.560	0.048808	3.1143
66.791	1.3120	0.47825	10.561	0.048869	3.1179
66.891	1.3120	0.47752	10.562	0.048931	3.1215
66.991	1.3120	0.47680	10.563	0.048993	3.1251
67.091	1.3120	0.47607	10.564	0.049054	3.1286
67.191	1.3120	0.47535	10.565	0.049116	3.1322
67.291	1.3120	0.47464	10.566	0.049178	3.1357
67.391	1.3120	0.47392	10.567	0.049239	3.1393
67.491	1.3120	0.47321	10.568	0.049301	3.1428
67.591	1.3120	0.47250	10.569	0.049363	3.1464
67.691	1.3120	0.47179	10.570	0.049425	3.1499
67.791	1.3120	0.47108	10.571	0.049486	3.1535
67.891	1.3120	0.47038	10.572	0.049548	3.1570
67.991	1.3120	0.46968	10.573	0.049610	3.1606
68.091	1.3120	0.46898	10.575	0.049672	3.1641
68.191	1.3120	0.46828	10.576	0.049733	3.1677
68.291	1.3120	0.46758	10.577	0.049795	3.1712
68.391	1.3120	0.46689	10.578	0.049857	3.1747
68.491	1.3120	0.46620	10.579	0.049919	3.1782
68.591	1.3120	0.46551	10.580	0.049981	3.1818

68.691	1.3120	0.46482	10.581	0.050042	3.1853
68.791	1.3120	0.46413	10.582	0.050104	3.1888
68.891	1.3120	0.46345	10.583	0.050166	3.1923
68.991	1.3120	0.46277	10.584	0.050228	3.1959
69.091	1.3120	0.46209	10.586	0.050290	3.1994
69.191	1.3120	0.46141	10.587	0.050352	3.2029
69.291	1.3120	0.46074	10.588	0.050414	3.2064
69.391	1.3120	0.46006	10.589	0.050475	3.2099
69.491	1.3120	0.45939	10.590	0.050537	3.2134
69.591	1.3120	0.45872	10.591	0.050599	3.2169
69.691	1.3120	0.45805	10.593	0.050661	3.2204
69.791	1.3120	0.45739	10.594	0.050723	3.2239
69.891	1.3120	0.45673	10.595	0.050785	3.2274
69.991	1.3120	0.45606	10.596	0.050847	3.2309
70.091	1.3120	0.45540	10.598	0.050904	3.2344
70.191	1.3120	0.45475	10.599	0.050961	3.2379
70.291	1.3120	0.45409	10.600	0.051017	3.2413
70.391	1.3120	0.45344	10.601	0.051074	3.2448
70.491	1.3120	0.45278	10.603	0.051130	3.2483
70.591	1.3120	0.45213	10.604	0.051187	3.2518
70.691	1.3120	0.45149	10.605	0.051244	3.2552
70.791	1.3120	0.45084	10.606	0.051300	3.2587
70.891	1.3120	0.45019	10.608	0.051357	3.2622
70.991	1.3120	0.44955	10.609	0.051413	3.2657
71.091	1.3120	0.44891	10.610	0.051470	3.2691
71.191	1.3120	0.44827	10.612	0.051527	3.2726
71.291	1.3120	0.44764	10.613	0.051583	3.2760
71.391	1.3120	0.44700	10.614	0.051640	3.2795
71.491	1.3120	0.44637	10.616	0.051697	3.2830
71.591	1.3120	0.44573	10.617	0.051753	3.2864

71.691	1.3120	0.44510	10.618	0.051810	3.2899
71.791	1.3120	0.44448	10.620	0.051866	3.2933
71.891	1.3120	0.44385	10.621	0.051923	3.2968
71.991	1.3120	0.44323	10.622	0.051980	3.3002
72.091	1.3120	0.44260	10.624	0.052036	3.3036
72.191	1.3120	0.44198	10.625	0.052093	3.3071
72.291	1.3120	0.44136	10.627	0.052150	3.3105
72.391	1.3120	0.44075	10.628	0.052206	3.3140
72.491	1.3120	0.44013	10.629	0.052263	3.3174
72.591	1.3120	0.43952	10.631	0.052320	3.3208
72.691	1.3120	0.43890	10.632	0.052376	3.3243
72.791	1.3120	0.43829	10.634	0.052433	3.3277
72.891	1.3120	0.43768	10.635	0.052489	3.3311
72.991	1.3120	0.43708	10.637	0.052546	3.3345
73.091	1.3120	0.43647	10.638	0.052603	3.3379
73.191	1.3120	0.43587	10.640	0.052659	3.3414
73.291	1.3120	0.43527	10.641	0.052716	3.3448
73.391	1.3120	0.43467	10.642	0.052773	3.3482
73.491	1.3120	0.43407	10.644	0.052829	3.3516
73.591	1.3120	0.43347	10.645	0.052886	3.3550
73.691	1.3120	0.43287	10.647	0.052943	3.3584
73.791	1.3120	0.43228	10.648	0.052999	3.3618
73.891	1.3120	0.43169	10.650	0.053056	3.3652
73.991	1.3120	0.43110	10.652	0.053113	3.3686
74.091	1.3120	0.43051	10.653	0.053169	3.3720
74.191	1.3120	0.42992	10.655	0.053226	3.3754
74.291	1.3120	0.42934	10.656	0.053283	3.3788
74.391	1.3120	0.42875	10.658	0.053339	3.3822
74.491	1.3120	0.42817	10.659	0.053396	3.3856
74.591	1.3120	0.42759	10.661	0.053453	3.3890

74.691	1.3120	0.42701	10.662	0.053509	3.3924
74.791	1.3120	0.42643	10.664	0.053566	3.3957
74.891	1.3120	0.42586	10.666	0.053622	3.3991
74.991	1.3120	0.42528	10.667	0.053679	3.4025
75.091	1.3120	0.42471	10.669	0.053736	3.4059
75.191	1.3120	0.42414	10.670	0.053792	3.4092
75.291	1.3120	0.42357	10.672	0.053849	3.4126
75.391	1.3120	0.42300	10.674	0.053906	3.4160
75.491	1.3120	0.42243	10.675	0.053962	3.4194
75.591	1.3120	0.42187	10.677	0.054019	3.4227
75.691	1.3120	0.42130	10.679	0.054076	3.4261
75.791	1.3120	0.42074	10.680	0.054132	3.4294
75.891	1.3120	0.42018	10.682	0.054189	3.4328
75.991	1.3120	0.41962	10.684	0.054245	3.4362
76.091	1.3120	0.41906	10.685	0.054302	3.4395
76.191	1.3120	0.41851	10.687	0.054359	3.4429
76.291	1.3120	0.41795	10.689	0.054415	3.4462
76.391	1.3120	0.41740	10.690	0.054472	3.4496
76.491	1.3120	0.41685	10.692	0.054529	3.4529
76.591	1.3120	0.41630	10.694	0.054585	3.4563
76.691	1.3120	0.41575	10.696	0.054642	3.4596
76.791	1.3120	0.41520	10.697	0.054698	3.4629
76.891	1.3120	0.41466	10.699	0.054755	3.4663
76.991	1.3120	0.41411	10.701	0.054811	3.4696
77.091	1.3120	0.41357	10.702	0.054895	3.4730
77.191	1.3120	0.41303	10.704	0.054952	3.4763
77.291	1.3120	0.41249	10.706	0.055009	3.4796
77.391	1.3120	0.41195	10.708	0.055066	3.4829
77.491	1.3120	0.41141	10.710	0.055123	3.4863
77.591	1.3120	0.41088	10.711	0.055180	3.4896

77.691	1.3120	0.41034	10.713	0.055237	3.4929
77.791	1.3120	0.40981	10.715	0.055294	3.4962
77.891	1.3120	0.40928	10.717	0.055351	3.4996
77.991	1.3120	0.40875	10.718	0.055408	3.5029
78.091	1.3120	0.40822	10.720	0.055465	3.5062
78.191	1.3120	0.40769	10.722	0.055521	3.5095
78.291	1.3120	0.40716	10.724	0.055578	3.5128
78.391	1.3120	0.40664	10.726	0.055635	3.5161
78.491	1.3120	0.40612	10.728	0.055692	3.5194
78.591	1.3120	0.40559	10.729	0.055749	3.5227
78.691	1.3120	0.40507	10.731	0.055806	3.5260
78.791	1.3120	0.40455	10.733	0.055863	3.5293
78.891	1.3120	0.40404	10.735	0.055920	3.5326
78.991	1.3120	0.40352	10.737	0.055977	3.5359
79.091	1.3120	0.40300	10.739	0.056034	3.5392
79.191	1.3120	0.40249	10.741	0.056090	3.5425
79.291	1.3120	0.40198	10.743	0.056147	3.5458
79.391	1.3120	0.40147	10.744	0.056204	3.5491
79.491	1.3120	0.40096	10.746	0.056261	3.5524
79.591	1.3120	0.40045	10.748	0.056318	3.5557
79.691	1.3120	0.39994	10.750	0.056375	3.5589
79.791	1.3120	0.39943	10.752	0.056431	3.5622
79.891	1.3120	0.39893	10.754	0.056488	3.5655
79.991	1.3120	0.39843	10.756	0.056545	3.5688
80.091	1.3120	0.39792	10.758	0.056642	3.5721
80.191	1.3120	0.39742	10.760	0.056699	3.5753
80.291	1.3120	0.39692	10.762	0.056756	3.5786
80.391	1.3120	0.39642	10.764	0.056813	3.5819
80.491	1.3120	0.39593	10.766	0.056870	3.5851
80.591	1.3120	0.39543	10.768	0.056926	3.5884

80.691	1.3120	0.39494	10.770	0.056983	3.5917
80.791	1.3120	0.39444	10.772	0.057040	3.5949
80.891	1.3120	0.39395	10.774	0.057097	3.5982
80.991	1.3120	0.39346	10.776	0.057154	3.6015
81.091	1.3120	0.39297	10.778	0.057211	3.6047
81.191	1.3120	0.39248	10.780	0.057268	3.6080
81.291	1.3120	0.39199	10.782	0.057324	3.6112
81.391	1.3120	0.39151	10.784	0.057381	3.6145
81.491	1.3120	0.39102	10.786	0.057438	3.6177
81.591	1.3120	0.39054	10.788	0.057495	3.6210
81.691	1.3120	0.39006	10.790	0.057552	3.6242
81.791	1.3120	0.38958	10.792	0.057609	3.6275
81.891	1.3120	0.38910	10.794	0.057665	3.6307
81.991	1.3120	0.38862	10.796	0.057722	3.6339
82.091	1.3120	0.38814	10.798	0.057779	3.6372
82.191	1.3120	0.38766	10.800	0.057836	3.6404
82.291	1.3120	0.38719	10.802	0.057893	3.6437
82.391	1.3120	0.38671	10.804	0.057950	3.6469
82.491	1.3120	0.38624	10.806	0.058006	3.6501
82.591	1.3120	0.38577	10.808	0.058063	3.6534
82.691	1.3120	0.38530	10.811	0.058120	3.6566
82.791	1.3120	0.38483	10.813	0.058177	3.6598
82.891	1.3120	0.38436	10.815	0.058234	3.6630
82.991	1.3120	0.38389	10.817	0.058291	3.6663
83.091	1.3120	0.38343	10.819	0.058347	3.6695
83.191	1.3120	0.38296	10.821	0.058404	3.6727