DEVELOPMENT OF CORRELATION FOR THERMOPHYSICAL PROPERTIES OF SUPERCRITICAL OXYGEN TO BE USED IN HIGH TEMPERATURE SUPERCONDUCTING MOTORS

DISSERTATION

in partial fulfillment of the requirement for the

award of the degree

of

MASTER OF TECHNOLOGY

in

MECHANICAL ENGINEERING

by

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LOVELY PROFESSIONAL UNIVERSITY, PUNJAB

CERTIFICATE

I hereby certify that the work which is being presented in the Dissertation entitled “**Development of Correlations for Thermophysical Properties of Supercritical Oxygen to be used in High Temperature Superconducting (HTS) Motors**” in partial fulfillment of the requirements for the award of degree of **Master of Technology** and submitted in the Department of Mechanical Engineering, Lovely Professional University, Punjab is an authentic record of our own work carried during period of dissertation under the supervision of **Mr. Raja Sekhar Dondapati, Asst. Professor**, Department of Mechanical Engineering, Lovely Professional University, Punjab.

The matter presented in this dissertation has not been submitted by me anywhere for the award of any other degree or to any other institute.

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This is to certify that the above statement mentioned by the candidate is correct to best of my knowledge.

Date:

Mr. Raja Sekhar Dondapati
(Supervisor)

The M.Tech Dissertation examination of **Development of Correlations for the Thermophysical Properties of Supercritical Oxygen to be used in HTS Motors** has been held on

Signature of the Examiner

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ABSTRACT

Supercritical regime of a fluid is a region above its critical point where distinct liquid and gaseous phases do not exist. In this project, thermophysical properties such as density, viscosity, thermal conductivity and specific heat of supercritical oxygen (SOX) will be studied to ensure the feasibility of SOX as a coolant. Supercritical temperature and pressure of oxygen is obtained from NIST web book and found to be 154.58K and 5.043MPa respectively. It was also found that above the critical point there is significant variation in the thermophysical properties of SOX. Further, mathematical representation of variation of density, viscosity, thermal conductivity and specific heat with temperature will be developed. The developed correlations can be beneficial for thermohydraulic analysis of High Temperature Superconducting (HTS) motors. Thermohydraulic analysis involves estimation of pressure drop due to flow of coolant and heat transfer from superconducting coils to refrigerating fluid. To extract heat, a suitable coolant must be chosen with respect to the critical temperature of the superconductor used in manufacturing of the coil. In view of development of superconductors which can work at higher temperature, the application of supercritical oxygen in HTS motors will be explore.

NOMENCLATURE

T_c	**Critical Temperature**
I_c	**Critical Current**
H_c	**Critical Magnetic Field**
HTS	**High Temperature Superconductor**
LTS	**Low Temperature Superconductor**
SCO	**Supercritical Oxygen**
LO_2	**Liquid Oxygen**
ρ	**Density**
μ	**Viscosity**
k	**Thermal Conductivity**
C_p	**Specific Heat**
ARE	**Average Relative Error**
SAR	**Sum of Absolute of Residual**
RE	**Relative Error**
AARE	**Average of Absolute of Relative Error**

1 Introduction

Population of the world is increasing day by day and correspondingly electrical consumption is also increasing. Electrical consumption in India is around 4.3% of the world whereas electrical generation in India is around 5% of the world [24]. Electrical energy is generated in power plants, transmitted to power grid and then to different power consumption sectors. In India, maximum electrical energy is transmitted to industries with the percentage of around 45% of total energy generated. While transmission and consumption of electrical energy, some part of the energy loses in the form of heat, sound, light or other forms of energy. The officially declared transmission and distribution (T&D) losses in India have gradually risen from 15% in the year of 1966-67 to about 23% in 1998-99. According to a study done by Electric power Research Institute (EPRI), total losses in various T&D system is around 7%-15.5% [25].

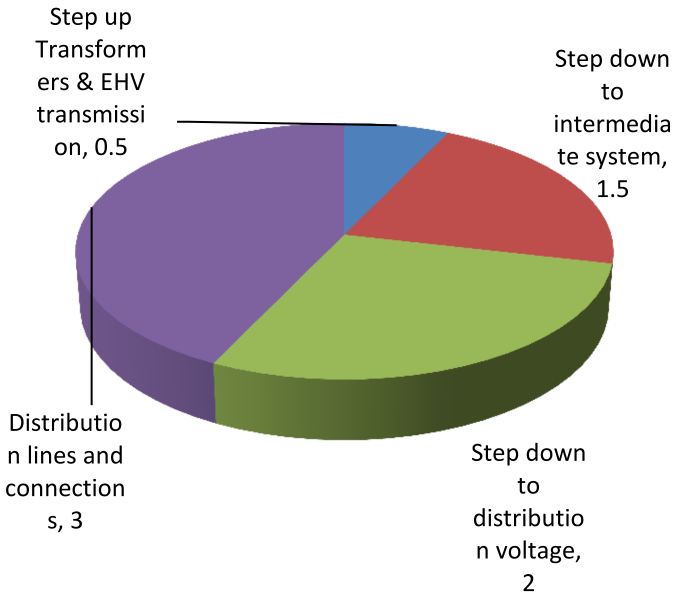

Figure 1.1.2 Distribution of Losses [21]

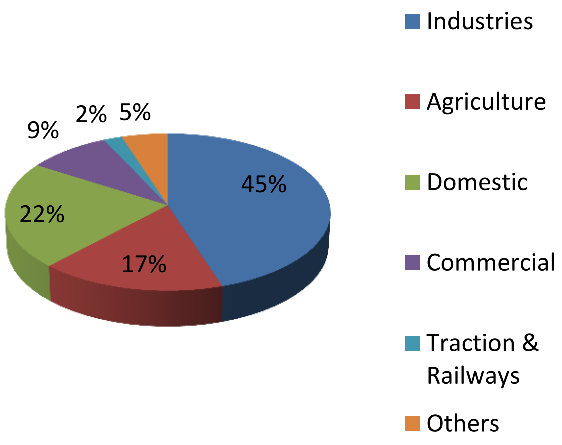

Figure 1.1.1 Sector wise Consumption of Electric Energy in India [21]

These losses occur because of improper load management, too many stages of transformations and use of poor quality of equipment. To minimize these losses research community has given a new noble concept, called superconductivity.

1.1 Superconductivity

Superconductivity is the phenomenon in which a material loses its resistance on cooling below the transition temperature (T_c). It was discovered in mercury by Dutch physicist Heike Kamerlingh Onnes in 1911. The temperature at which mercury showed superconductivity was found near about 4.2 K. Subsequently, many metals, alloys and intermetallic compounds were found to exhibit superconductivity. The highest T_c known was limited to 23.2 K in Nb_3Ge alloy.

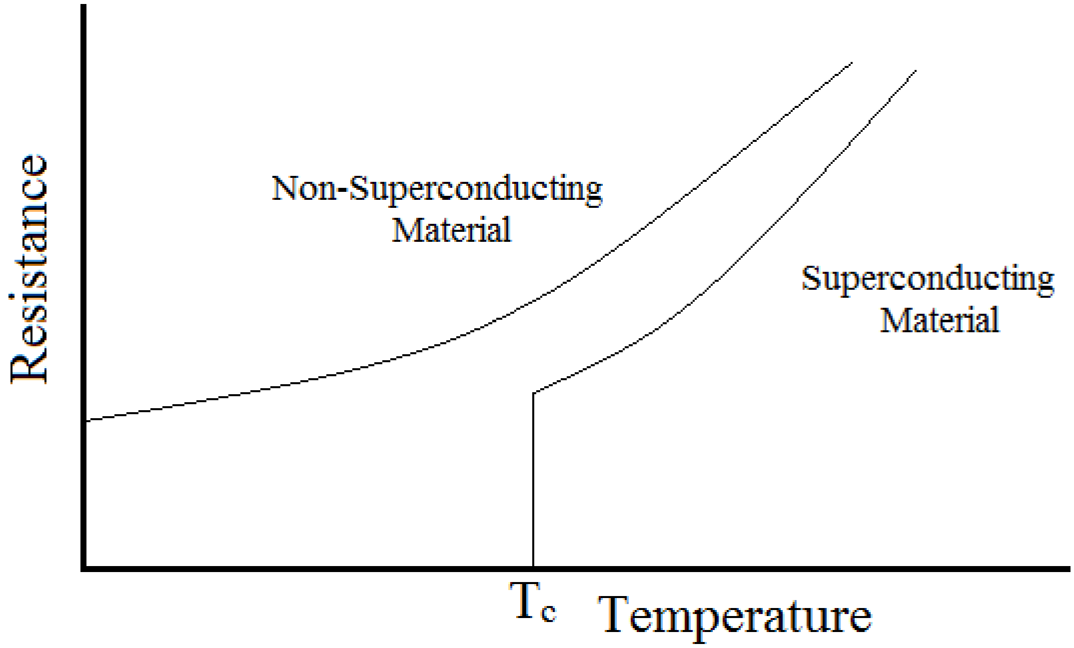

Figure 1.1.3 Comparison between Superconducting and Non-Superconducting materials

However, in 1986, Bednorz and Muller discovered high temperature superconductivity (HTS) in ceramic cuprate oxides. The value of T_c was near about 30 K. Superconductors above 30 K temperature is called high temperature superconductors. Till now superconductivity has been achieved till the temperature of 133 K [4]. In addition to T_c , the critical field H_c and critical current density J_c are two other parameters that define a critical surface below which the superconducting phase can exist. T_c and H_c are thermodynamic properties that for a given superconducting material are invariant to metallurgical processing while J_c is not.

Superconductors have many advantages as compared to ordinary conductors. First advantage is power and cost efficiency, which is due to the negligible energy losses that occur in superconductors. Its efficiency also leads to environmental benefits, including reduced fuel consumption and CO_2 emission that result from lower electrical losses. By using superconductors, the weight and size of electrical devices becomes smaller with same specifications. Moreover, a superconductor can cause a magnet to levitate above it because it repels the magnetic field. This phenomenon is called Meissner Effect. It describes the absence of magnetic field within the superconductor. This diamagnetism behaviour of a superconductor is in fact more fundamental than the complete absence of electrical resistivity. On this principle MagLev trains work.

Superconductivity is also described by Meissner Effect. The Meissner effect describes the absence of magnetic field within the bulk of a superconductor. This complete diamagnetism of a superconductor is in fact more fundamental than the complete absence of electrical resistivity. On the principle of meissner effect, MagLev trains work.

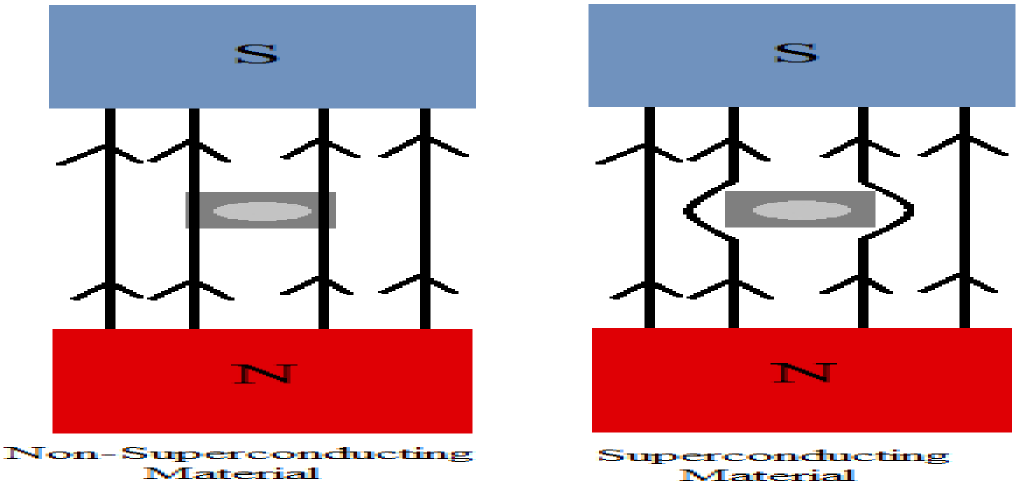

Figure 1.1.4 Meissner Effect

Superconductivity was introduced by the research community to minimize the losses in various applications. These days superconductivity has many applications. Some of them are HTS Generator, HTS Cables, Superconducting Magnetic Energy Storage (SMES), Fault Current Limiter (FCL) and HTS Motors. Earlier we have discussed that in India, maximum electrical energy is transmitted to industries, to run electrical motors. Application of superconductivity in electrical motors has gained much attention by the researchers. Superconducting motors are the motors that employ HTS windings in place of conventional copper coils. Because HTS wire can carry significantly larger currents than can copper wire, these windings are capable of generating much powerful magnetic fields in a given volume of space. Motors consist of two main parts, a rotor and a stator. The interaction between the magnetic field provided by the rotor and the alternating currents (AC) flowing in the windings result in electromagnetic torque. Conventional motors use copper windings and an iron core to increase the magnitude of the air gap flux density created by copper windings. Iron has a nonlinear magnetic behavior and saturates at a flux density of 2 tesla thus, limiting the electromagnetic torque. In HTS motors, the copper rotor windings can be replaced with superconducting windings with a resulting current density 10 times greater without any resistive losses. The superconducting motor is virtually an "air core" where the stator is constructed without the iron teeth of a conventional motor. This type of construction eliminates core saturation and iron losses. Figure 1.4 shows an actual 5MW HTS motor designed and built by American Superconductor (AMSC) and Figure 1.5 shows a comparison between the construction of a conventional motor and an HTS motor [13].

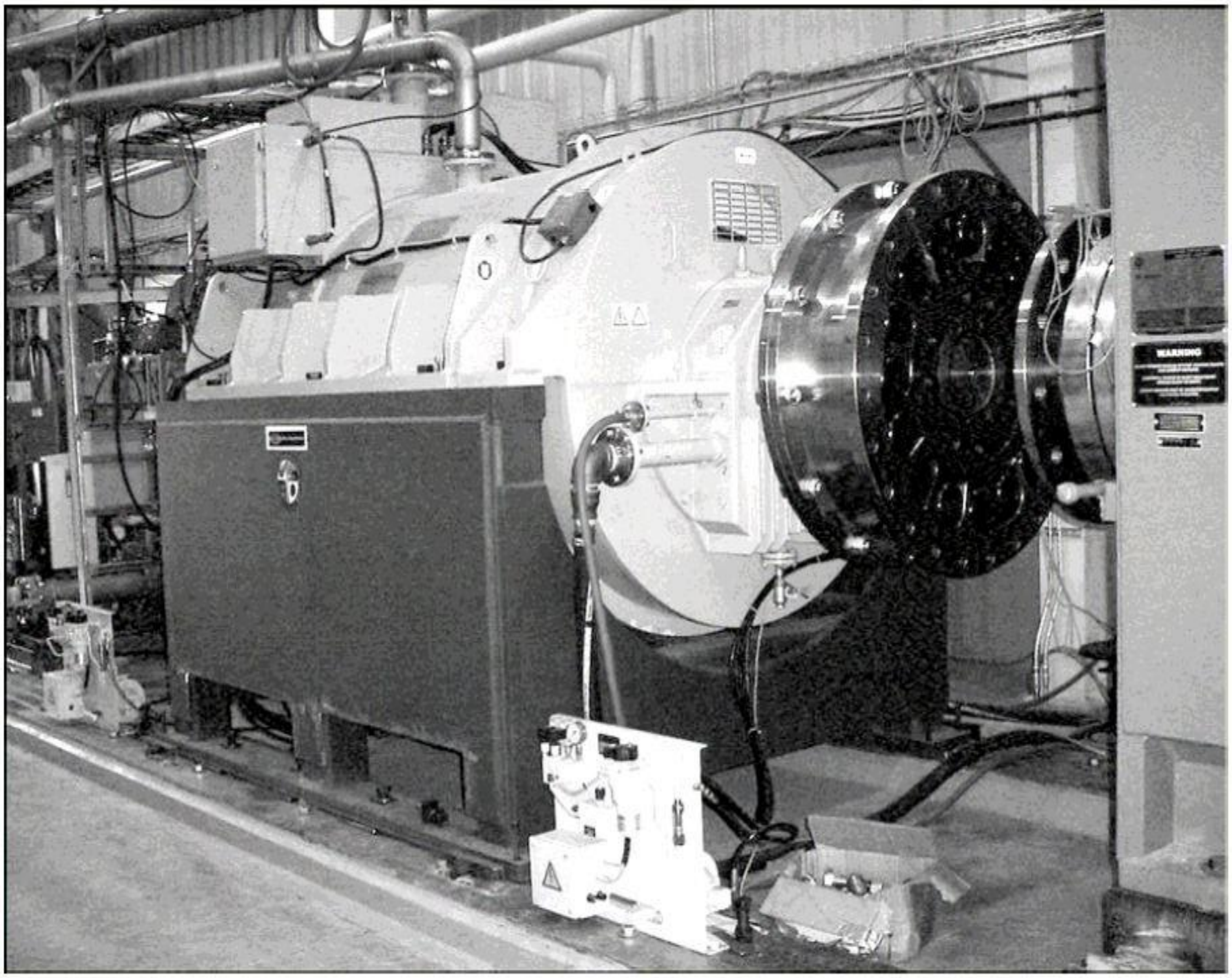

Figure 1.1.5 AMSC 5MW HTS Motor [13]

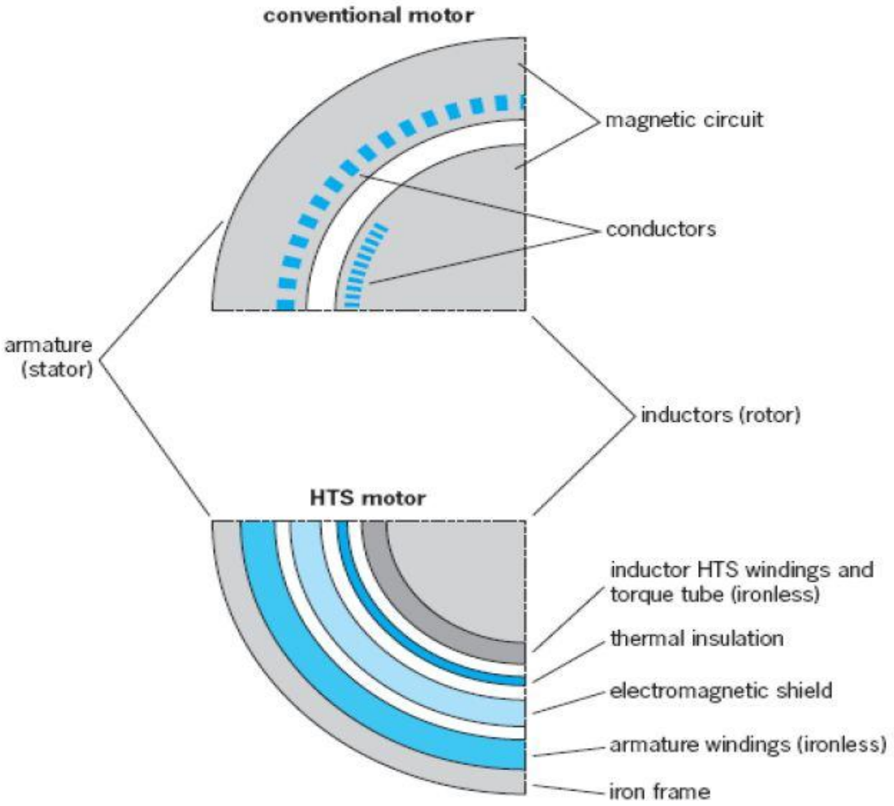

Figure 1.1.6 Comparison between conventional synchronous motor and HTS synchronous motor [13]

This motor has many benefits:

- Less vibration and noise
- Smaller size and weight
- Increased stability
- High power to weight ratio

As discussed, superconductivity is achieved till the temperature of 133K which is much below than room temperature. So, a cooling system is required to extract the internal heat generated during the working. These types of cooling system are also called cryogenic system. Cryogenic system of a superconducting system requires a cryogen. There are three types of cryogen; Inert Gases, Flammable Gases & Oxygen. A cryogen must have high specific heat, high thermal conductivity, high density and low viscosity. These days, liquid cryogens are extensively used in cryogenic systems but they create some problems also. There is multiphase flow in the cryogenic systems using liquid cryogens. Moreover, when conventional cryogenic liquids form a gas, it expands to a much larger volume, for example, 1 litre of liquid nitrogen vaporizes to 695 litres of nitrogen gas when warmed to the temperature of 21°C. Moreover, cooling fluids like liquid carbon monoxide can release large quantities of carbon monoxide gas, which can cause death immediately. Materials that are usually considered non-combustible, may burn in the presence of liquid oxygen. There is a chance of explosion, if liquid oxygen are being used [17]. To minimize these problems research communities have suggested that instead of using liquid or gaseous cryogen, supercritical cryogens can also be used.

1.2 Supercritical Fluid

A fluid is said to be supercritical when its temperature and pressure exceed its critical temperature and pressure. In P-T space, it can be seen that the liquid and vapor coexist after the critical point. In the figure 1.2, the critical isotherm $T = T_c$ and the critical isobar $P = P_c$ are indicated. If the liquid is heated at a constant pressure exceeding the critical pressure, it expands and reaches a vapour like state without undergoing phase transition. Andrews and Vander Waals called this phenomenon, the continuity of states [16]. Supercritical fluids exhibits significantly lower viscosities than liquids, which provide favourable flow properties. Moreover, supercritical fluids are inert, available in high purity, non-toxic and relatively inexpensive [18]. Oxygen is the most abundant element in nature as well as its extraction is also very easy. Moreover, converting

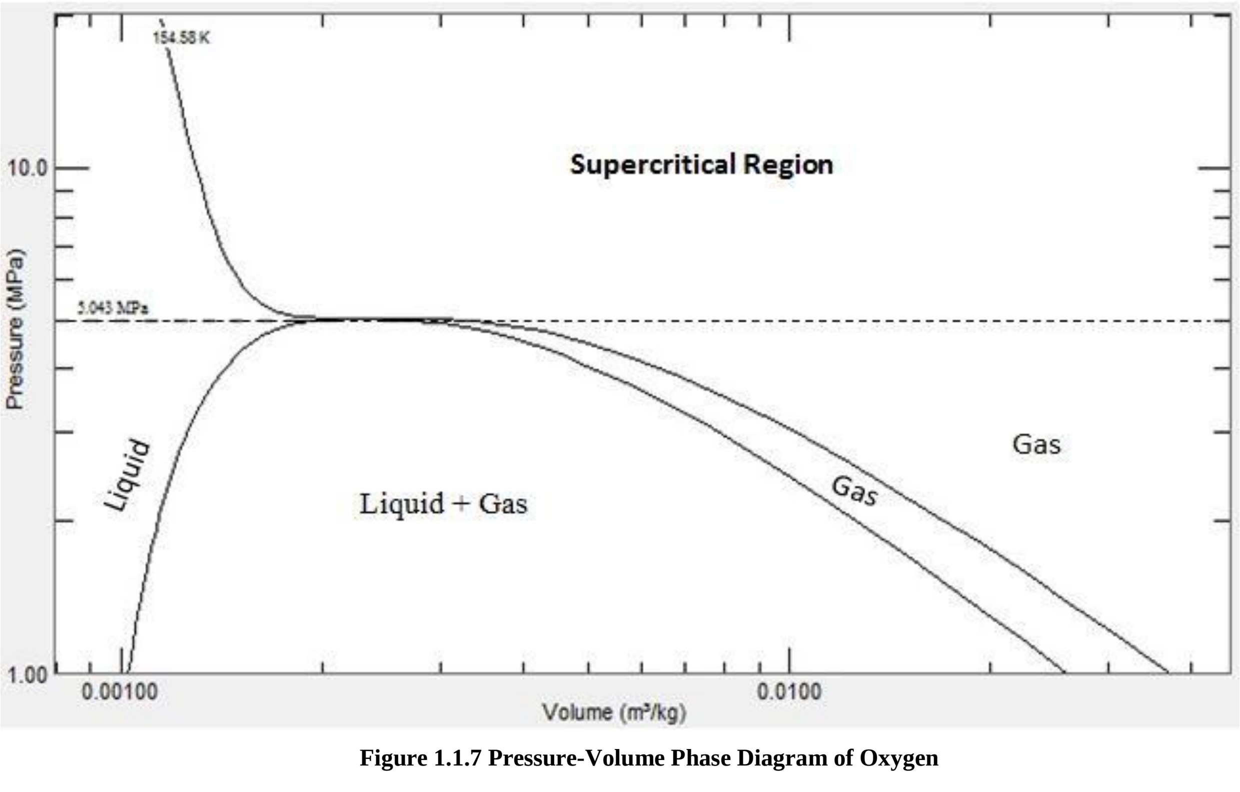

Figure 1.1.7 Pressure-Volume Phase Diagram of Oxygen

oxygen into supercritical oxygen requires less enthalpy change as compared to that of nitrogen, argon and hydrogen and maintaining the critical pressure of oxygen is easy as compared to that of carbon dioxide and ammonia.

Table I Critical condition of some fluids [18]

Fluid	Critical Temperature (T_c)	Critical Pressure (P_c)
Nitrogen	**126.19 K**	**3.3958 MPa**
Oxygen	**154.58 K**	**5.043 MPa**
Argon	**150.69 K**	**4.863 MPa**
Hydrogen	**33.190 K**	**1.315 MPa**
Carbon Dioxide	**304.13 K**	**7.3773 MPa**
Ammonia	**405.40 K**	**11.333 MPa**

2 Scope of Study

We know that, High Temperature Superconductors (HTS) play a vital role in energy conservation sector. Replacement of conventional electrical devices with HTS devices may increase the performance of whole electrical system. HTS devices need a cooling system to maintain the critical temperature. HTS systems are cooled by various cryogenic coolants in order to nullify the generated heat in the system. The properties of these coolants are very sensitive with temperature. Hence, it is very important to study the properties which are affected by the temperature. These properties are called thermophysical properties. In a formal manner we can say that, thermophysical properties are the properties affecting the transfer and storage of heat that vary with temperature, pressure and composition, without altering the material’s chemical identity. Density, Viscosity, Thermal Conductivity and Specific Heat are the four thermophysical properties of a fluid.

This study undergoes the analytical work of thermophysical properties of supercritical oxygen (SOX). Mathematical equations will be developed at the critical pressure and taking temperature as varying parameter. Moreover, the cooling capacity of few other supercritical fluids will be discussed.

3 Literature Review

As discussed, it is very important to study thermophysical properties of a cryogen. It is because of the fact that while working two types of losses occurs in cryogen; Pressure loss and thermal loss. From the concept of thermodynamics, it is clear that with change in pressure there is change in density of the fluid as well as viscosity is also gets affected. So, it can be said that density and viscosity have relevance to pressure loss. Moreover, as we know thermal conductivity and specific heat have temperature dependences, so due to heat losses there will be some change in the temperature of cryogen. So, before putting emphasis on thermophysical properties, it is very important to study these two losses.

3.1 Cryogenics and Supercritical Fluid Technology

- **Raja Sekhar Dondapati and V.V. Rao [2013**], in their research paper "pressure drop and heat transfer analysis of long length internally cooled HTS cables" [9] have done pressure drop and heat transfer analysis and found that the fluctuations cause the turbulence in the flow of cryogen which results in the higher rate of shear stress at the walls. Moreover, at higher Reynolds numbers, the friction factors are less as compared to those at lower Reynolds numbers. And they found that to achieve efficient heat transfer, twisted tapes can be inserted into the cryogen path.
- **Yanhua Yang, Xu Cheng, Shanfang Huang [2009],** in their research paper "A new heat transfer correlation for supercritical fluids" [14] has indicated that the heat transfer of supercritical fluids shows abnormal behavior as compared to that of conventional fluid. They developed a correlation for the heat transfer application of supercritical fluids. The new correlation can be applied to both normal and Heat Transfer Deterioration (HTD) conditions. It was found that the new correlation shows better results as compared to the earlier developed correlations.
- **Z.Q. Long, P.Zhang [2013],** in their research "Natural convective heat transfer of supercritical helium in a closed vertical cylinder" [15] have indicated that the natural convective heat transfer of supercritical helium in a closed vertical cylinder gives excellent heat transfer performance as compared with that of conventional gases. Moreover, it can be enhanced by increasing the helium charging amount. In the Rayleigh number range (5 X

10^{10} to 2 X 10^{14}), the Nusselt number increases almost exponentially with the Rayleigh number.

- **Azad Jarrahian, Ehsan Heidaryan [2012]**

  They have done research on supercritical carbon dioxide. They have developed a correlation to estimate the thermal conductivity of supercritical carbon dioxide by using residual concept. They developed correlation by using 668 data points from the literature as well as from NIST. This correlation is valid for the temperature of 310 to 960 K and pressure range between 7.4 and 210 MPa. The error was found to be around 2.7 and 2.4% in the comparison with literature and NIST respectively. The correlation is given by:

$$\lambda = \frac{A_1 + A_2 p + A_3 p^2 + A_4 Ln(T) + A_5 Ln(T)^2}{1 + A_6 p + A_7 Ln(T) + A_8 Ln(T)^2 + A_9 Ln(T)^3}$$

  where λ is thermal conductivity, p is pressure and T is temperature.

  Moreover, they have modified the Redlich-Kwong equation of state for supercritical carbon dioxide and found that the new equation of state possesses less error as compared to that of Peng-Robinson, Redlich-Kwong and Van der Waals EOS.

- **Ali Akbar Amooey [2014],** in his research paper “ A simple correlation to predict thermal conductivity of supercritical carbon dioxide” [2] has developed a simple correlation to estimate the thermal conductivity of supercritical carbon dioxide and found that the newly development correlation gives better results as compared to the earlier correlations.
- **Raja Sekhar Dondapati, V.V. Rao [2014],** in their research paper “Entropy generation minimization (EGM) to optimise mass flow rate in dual channel cable-in-conduit conductors (CICCs) used in fusion grade magnets” [10] have indicated that the factors that affect entropy generation in CICC include heat transfer, flow with friction and mixing of flow streams. Moreover, optimum mass flow rate was calculated at which heat transfer rate is highest.

  In dual channel CICC, entropy generation due to thermal gradient dominates as compared to that of velocity gradient.

3.2 High Temperature superconducting Motors

- **Anbin Chen, Xiaokun Liu, Fengyu Xu, Jiwei Cao, Liyi Li [2010],** in their paper “Design of the cryogenic system for a 400kW experimental HTS synchronous motor” [1] have indicated that the designed model has the heat load of 730.4 W. This heat load is the sum of heat leaks from the surroundings and internal heat generation in the device. By taking the basis of heat load, cryogenic system was designed.
- **S.K. Baik, M.H. Sohn, E.Y. Lee, Y.K. Kwon, T.S. Moon, H.J. Park, Y.C. Kim [2006],** in their paper “Effect of synchronous reactance and power factor on HTS synchronous machine design and performance” [12] have concluded that as synchronous reactance becomes smaller, it is possible to get better design results and performance characteristics at steady state condition. Moreover, smaller synchronous reactance increases armature current at transient states such as fault condition and motor starting.
- **Minseok Joo [2004],** in his paper “Dynamic control of large scale high temperature superconducting synchronous motor” has indicated that the control strategy of starting the high temperature superconducting synchronous motor with constant field windings is to give gating signal commands during accelerating period. This proposed model provides more effective way to implement a model based approach to designing and testing the high temperature superconducting motor system.
- **Sang-Ho Lee, Jung-Pyo Hong, Young-Kil Kwon, Young-Sik Jo, Seung-Kyu Baik [2008],** in their paper “Study on homopolar superconductivity synchronous motors for ship propulsion applications” [8] have indicated that superconducting synchronous motors compared with conventional motors can reduce motor size and has higher efficiency.

4 Objective of Study

The main objective of this research is to check the feasibility of Supercritical Oxygen as a coolant in the cryogenic cooling system of HTS Motors. This can be done by studying the thermophysical properties of the fluid at different temperatures. Till now, managing the values of thermophysical properties at different temperatures has been a great challenge for the researchers, so in this research work correlations has been developed to minimize the tedious task of data management. Moreover, feasibility of Supercritical Oxygen as a cryogen is also a main objective of the study.

5 Research Methodology

In this research, analysis of thermophysical properties of Supercritical Oxygen will be done and its results will be used in the cooling system of HTS motors. So, it can be said that the research type fundamental as well as applied. It is very important to choose a proper method while doing a research. Since, this project involves development of correlations so extraction of data from a trusted source is of prior importance. National Institute of Standards and Technology (NIST) is a part of the U.S. Department of Commerce and is a physical science laboratory. It has a web book which contains data about thermophysical properties of various fluids. So, extraction of data can be done from NIST web book. From the extracted data, it was found that near the critical point there is significant change in the property value. To describe that change, mathematical model would be required. In this project, the mathematical modeling will be done by using residual concept. Since, there is significant variation in property values so different correlations for different intervals will be required to develop. Different intervals will be determined by hit & trial method. In the application of results, analyses will be done on the cooling pipe of HTS motor using COMSOL Multiphysics v3.5. The design parameters of the cooling pipe will be taken from an existing model.

6 Results and Discussions

In this research four thermophysical properties i.e. Density, Viscosity, Thermal Conductivity and Isobaric Specific Heat of SOX has been studied. Fig. 6.1 shows the variation of different properties at different pressures. It can be seen that with increase in pressure value for density and viscosity also increases but it is not same for thermal conductivity and isobaric specific heat. The value of thermal conductivity and specific heat respectively are maximum at critical pressure. And, these are the two properties which are taken into account at highest priority while selecting a proper coolant. Hence, P_c has been chosen as the working pressure for SOX.

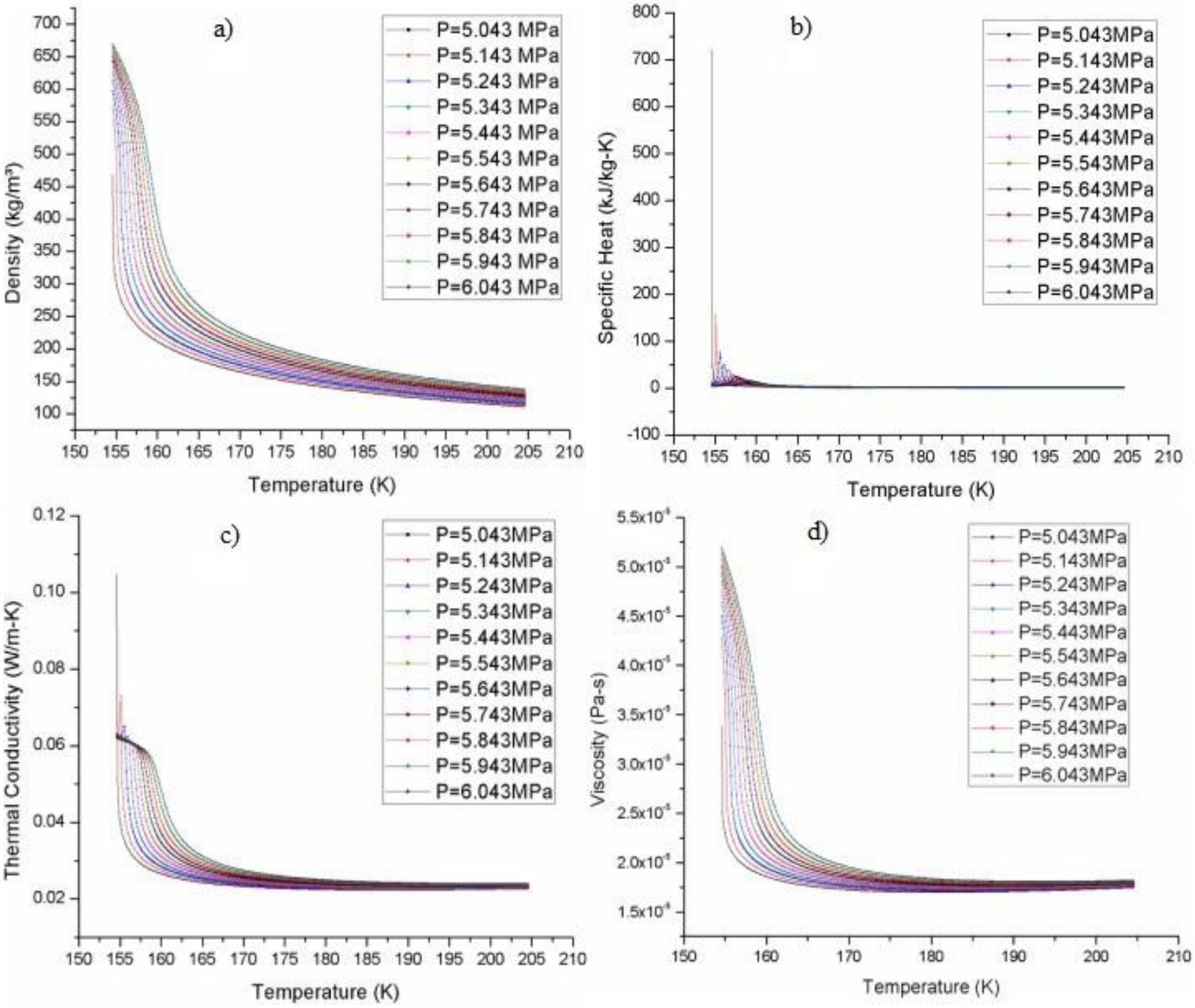

Figure 6.1 Variation in Thermophysical Properties at different pressures

501 data points for each property were extracted at P_c from NIST web book. These data were taken from temperature of 154.58 K (T_c) to 204.58 K with the increment of 0.1 K. From table II, it can be seen that there is significant variation in the property value just after critical point. Different thermophysical properties have been discussed below.

Table II Property Values of SOX at P_c and just after critical point

	Density (kg/m^3)	Viscosity (Pa-s)	Thermal Conductivity (W/m-K)	Isobaric Specific Heat (kJ/kg-K)
T = 154.58 K	466.41	3.3759 E-5	0.10442	719.48
T = 154.68 K	339.76	2.5015 E-5	0.051173	46.849
T = 154.78 K	323.44	2.4046 E-5	0.045666	28.453
T = 154.88 K	312.82	2.3436 E-5	0.042725	21.317
T = 154.98 K	304.77	2.2985 E-5	0.040746	17.395
T = 155.08 K	298.22	2.2625 E-5	0.039269	14.873
T = 155.18 K	292.68	2.2326 E-5	0.038097	13.097
T = 155.28 K	287.85	2.2069 E-5	0.037132	11.769
T = 155.38 K	283.56	2.1843 E-5	0.036313	10.734
T = 155.48 K	279.69	2.1643 E-5	0.035605	9.9011
T = 155.58 K	276.17	2.1463 E-5	0.034983	9.2144

6.1 Themophysical Properties

6.1.1 Density

Critical point is the point at which domination of liquid and gaseous state are equal, so fluid shows dual nature. But beyond critical point, there is domination of gaseous state and in gases as molecules get heated, their entropy increases. With increase in randomness, volume of the fluid increases. This can be a reason for decrease in density beyond critical point. Density data points were very much scattered hence whole temperature range was divided into three parts. The developed correlation is given by equation (1).

$$\rho = \frac{(\rho_0 + \mathrm{T})}{(\rho_1 + \rho_2 * \mathrm{T})} \tag{1}$$

Here ρ_0, ρ_1 and ρ_2 are correlation coefficients and are given in Table III. Figure 6.2 shows two curves, one for NIST value and other for fitted value with error bars.

To study more about the correlation, derivative of equation (1) was taken with respect to temperature.

$$\frac{d\rho}{dT} = \frac{\rho_1 - \rho_0 \rho_2}{(\rho_1 + \rho_2 T)^2}$$

(2)

For determining maxima or minima, first derivative of equation (1) i.e. equation (2) was taken equal to 0.

$$\frac{d\rho}{dT} = 0$$

$$\rho_1 = \rho_0 * \rho_2$$

(3)

Equation (3) is independent of T. This means

$$\frac{d^2\rho}{dT^2} = 0$$

(4)

Equation (4) shows that there is a point of inflexion at maxima and minima.

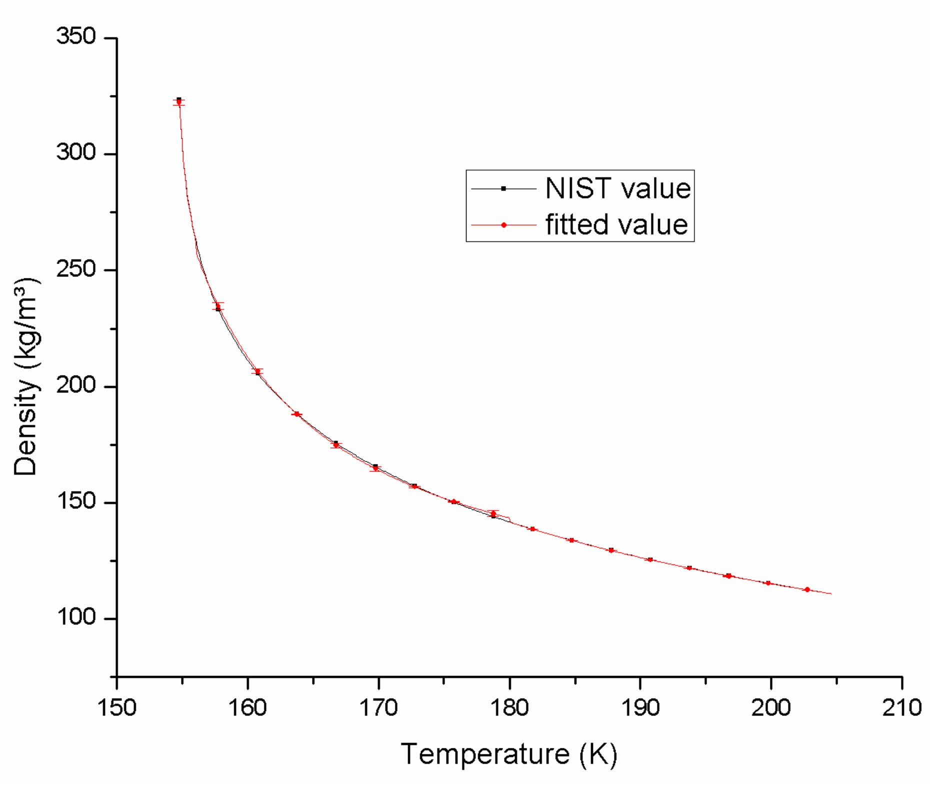

Figure 6.2 Density vs Temperature of SOX with fitted curve

6.1.2 Viscosity

In each fluid there is intermolecular bond between the two molecules. And the strength of intermolecular bonds determines the viscosity of the fluid. The breaking down of intermolecular bond with heat addition results in decrease of cohesive force between fluid particles which further affects the viscosity of the fluid. Beyond critical point domination of gaseous state results in decrease in viscosity. In viscosity, variation was scattered such that it was difficult to develop a single correlation for the entire temperature range. Hence, range was divided into two parts and two correlations were developed for each range. The developed correlations are given by equation (5) & (6).

For temperature up to 179.98 K

$$\mu = \frac{(\mu_0 + \mathrm{T})}{(\mu_1 + \mu_2 * \mathrm{T})} \tag{5}$$

For temperature range 179.98 K ≤ T ≤ 204.98 K

$$\mu = \left(\mu_0 + \mu_1 * \mathrm{T} + \mu_2 * \mathrm{T}^2\right)^{-1}$$

(6)

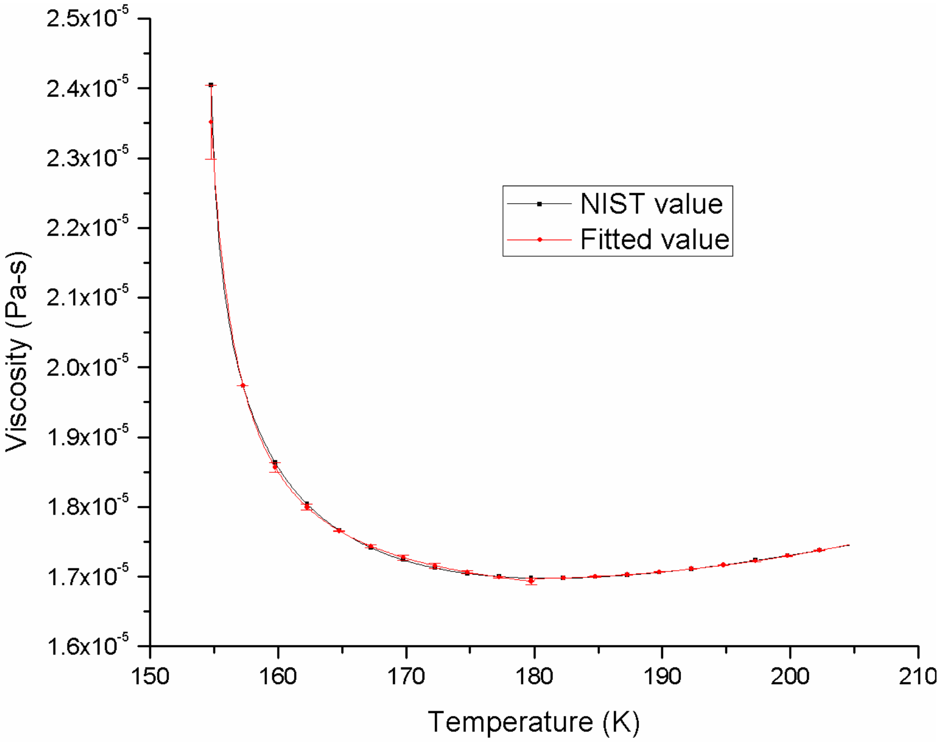

Figure 6.3 Viscosity vs Temperature of SOX with fitted curve

Here μ_0, μ_1 and μ_2 are correlations coefficients and given in Table III. Figure 6.3 shows the distribution of viscosity with temperature.

Type of equation of equation (5) is same as equation (1). Hence, analysis using differentiation of equation (5) would be same. This means, there will lay a point of inflexion at the maxima or minima of the curve.

The first derivative of equation (6) was found as

$$\frac{d\mu}{dT} = \frac{-1*(\mu_1 + 2\mu_2 * T)}{(\mu_0 + \mu_1 * T + \mu_2 T^2)^2}$$

(7)

For maxima,

$$\frac{d\mu}{dT} = 0$$

So, $T = \frac{-\mu_1}{(2*\mu_2)}$ (8)

By putting values of μ_1 and μ_2, the value of T becomes 177.456173 K. Using this value double differentiation gives negative value. Hence, this can be conclude that the analysis using differentiation gives the maxima at temperature 177.456173 K. Moreover, after doing error analysis it was found that the difference in NIST value and fitted values becomes significant, so this point was not included while developing correlations.

6.1.3 Thermal Conductivity

Thermal Conductivity is a property of a substance which is responsible for the transfer of heat energy from one molecule to another. It is directly proportional to intermolecular distance. Just after the critical point, with the domination of gaseous state intermolecular bond breaks and hence increase in intermolecular distance can be noted. This effect can be a cause for the decrease in thermal conductivity. Developed correlation can be given by equation (9).

$$k = \frac{k_0 + k_1 * T}{k_2 + T}$$

(9)

Here k_0, k_1 and k_2 are correlation coefficients and are given in Table III. Figure 6.4 shows the variation of thermal conductivity with fitted curve.

To study more about the correlation, derivative was taken with respect to temperature and was found to be

$$\frac{dk}{dT} = \frac{k_2 * k_1 - k_0}{(k_2 + T)^2}$$

(10)

For maxima or minima, first derivative was taken equal to zero. It was found that

$$k_0 = k_2 * k_1 \qquad (11)$$

Equation (11) is independent of T. This means

$$\frac{d^2 k}{dT^2} = 0$$

(12)

This shows the point of inflexion at maxima or minima.

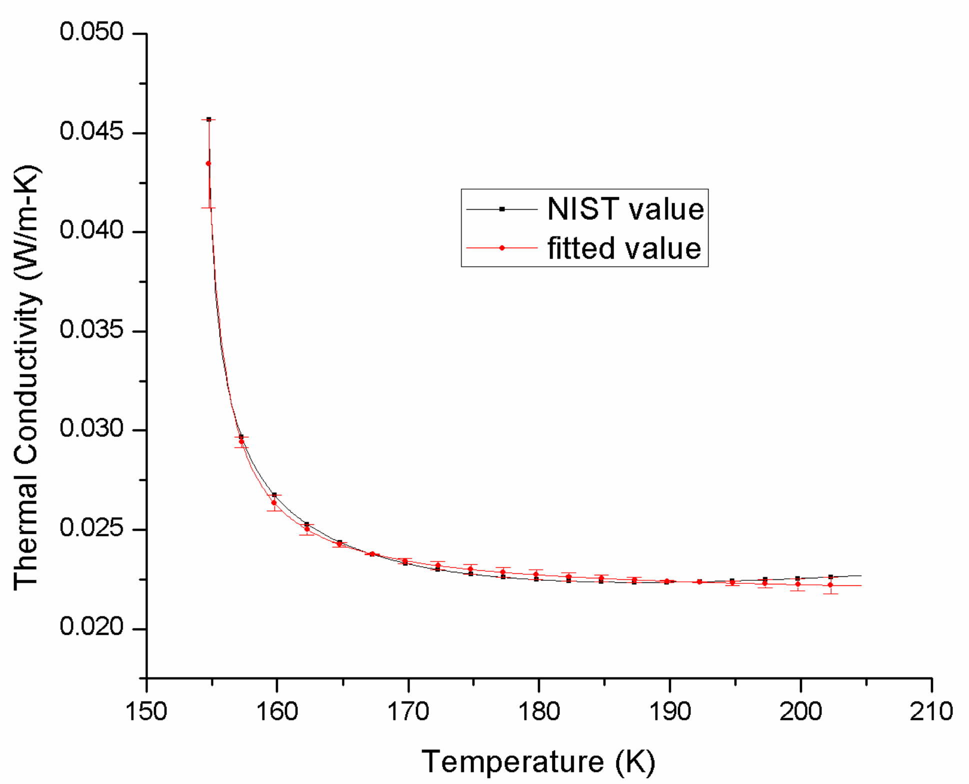

Figure 6.4 Thermal Conductivity vs Temperature with fitted curve.

6.1.4 Isobaric Specific Heat

Specific heat is the property of a substance which indicates the amount of heat required to raise the temperature of a unit mass substance by 1 K. Beyond critical point with the domination of gaseous property, specific heat decreases. The developed correlation for the specific heat is given by equation (13).

$$c_p = \frac{(c_0 + T)}{(c_1 + c_2 * T)}$$

(13)

Here c_0, c_1 and c_2 are correlation coefficients and given in Table III. Figure 6.5 shows the variation of specific heat with temperature and fitted curve.

Equation (13) is similar to equation (1). Hence, analysis using differentiation would be the same. So, there will lay a point of inflexion at the maxima or minima.

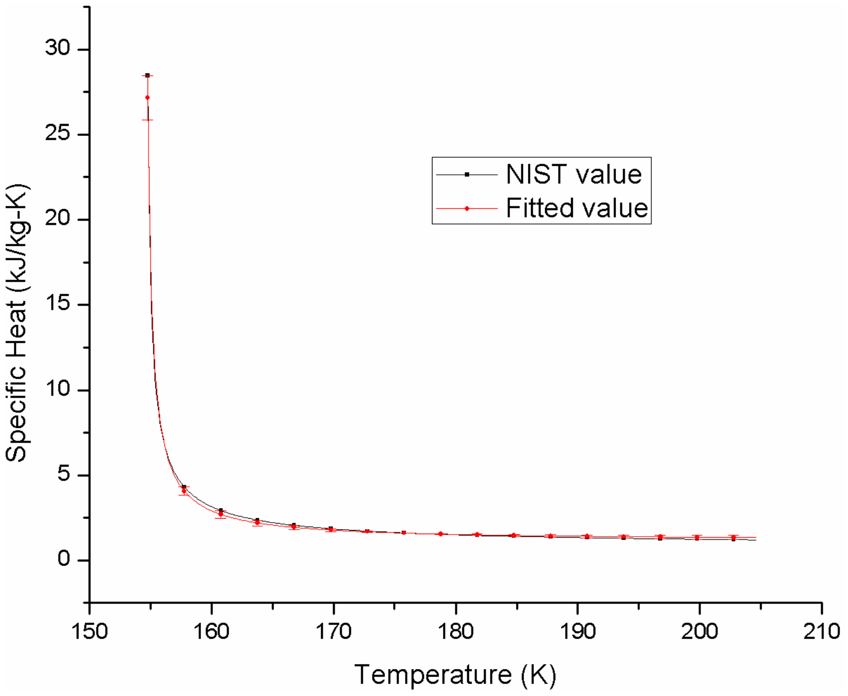

Figure 6.5 Isobaric Specific Heat vs Temperature with fitted curve

Table III Values of correlation coefficients with units

Property	Temperature Range	Correlation Coefficients

Density	**154.78K ≤ T ≤ 155.98K**	ρ_0 **= -153.25792 K** ρ_1 **= -0.71191** K-m^3/kg ρ_2 **= 0.00463** m^3/kg
	155.98K < T ≤ 179.98K	ρ_0 **= -127.45094 K** ρ_1 **= -1.55271** K-m^3/kg ρ_2 **= 0.01066** m^3/kg
	179.98K < T ≤ 204.58K	ρ_0 **= 34.10029 K** ρ_1 **= -3.17982** K-m^3/kg ρ_2 **= 0.02606** m^3/kg
Viscosity	**154.78K ≤ T ≤ 179.98K**	μ_0 **= -151.5439 K** μ_1 **= -9.3343E6 K/Pa-s** μ_2 **= 61196.030 (Pa-s)$^{-1}$**
	179.98K < T ≤ 204.58K	μ_0 **= -11908.656 (Pa-s)$^{-1}$** μ_1 **= 798.49818 (K-Pa-s)$^{-1}$** μ_2 **= -2.24998 (K^2-Pa-s)$^{-1}$**
Thermal Conductivity	**154.78K ≤ T ≤ 204.58K**	k_0 **= -3.27795 W/m** k_1 **= 0.02157 W/m-K** k_2 **= -153.38396 K**
Isobaric Specific Heat	**154.78K ≤ T ≤ 204.58K**	c_0 **= -145.72924 K** c_1 **= -135.17813 kg-K^2/kJ** c_2 **= 0.87551 kg-K/kJ**

6.1.5 Error Analysis

To validate the developed correlations, error analysis was done on each correlation. To minimize the error of the equations, two data points (at T = 154.58K and T = 154.68K) for each property had been omitted. This means, above correlations are valid in the temperature range of 154.78 K to 204.58 K. For error analysis two data sets were taken, first NIST data and second predicted data or fitted value. Moreover, in order to evaluate the proposed correlations, statistical parameters were used. The arithmetic average of absolute values of relative errors (AARE %), which is given by equation (14)

$$AARE\% = \frac{100}{N}\sum_{i=1}^{499}\left|\frac{\lambda_i^{\exp} - \lambda_i^{cal}}{\lambda_i^{\exp}}\right|$$

(14)

is an indication of accuracy of the correlations. Since, AARE% deals with the relative error, another parameter Sum of Absolute of Residual (SAR) indicates reliability of correlation. SAR defined as in equation (15).

$$SAR = \sum_{i=1}^{499}\left|\lambda_i^{\exp} - \lambda_i^{cal}\right|$$

(15)

The AARE% and SAR values for developed correlations are given in Table IV. Low value of AARE% shows less error and lower value of SAR shows high reliability of the developed correlation. Moreover, maximum value of absolute of relative error for is 1.6% at T = 156.08 K, 2.21% at T = 154.78 K, 4.85% at T = 154.78 K and 10.7% at T = 204.58 for density, viscosity, thermal conductivity and specific heat respectively.

Table IV AARE% & SAR values for the developed correlations

Property	AARE %	SAR
Density	0.2449	219.019
Viscosity	0.1203	$1.117*10^{-5}$
Thermal Conductivity	0.8855	0.106826
Specific Heat at Const. Pressure	5.3572	53.48412

6.2 Comparison of cooling capacities of different supercritical fluid

Before using a fluid as a cryogen, it is important to find the cooling capacity of that fluid. In this research, cooling capacity of Supercritical Oxygen was compared with the cooling capacities of other supercritical Fluids. Supercritical Nitrogen is the most abundant gas in atmosphere and Supercritical Argon has the critical temperature near to that of Oxygen. Hence, Supercritical Nitrogen and Supercritical Argon were used for the comparison of cooling capacities. Cooling capacities of the fluids can be calculated using equation (16).

$$Q_{cc} = \dot{V} \rho C_p * \Delta T$$

(16)

Density and isobaric specific heat of Supercritical Nitrogen and Supercritical Argon at critical point are given in Table V.

Table V Density and Specific Heat of Supercritical Nitrogen and Supercritical Argon at critical point

	Density	**Isobaric Specific Heat**
Supercritical Nitrogen	**342.67**	**729.99**
Supercritical Argon	**484.83**	**511.11**

Since, critical temperatures are different so, unit temperature difference was taken to calculate the cooling capacities while mass flow rate was taken to be in the range of 5.5-8.0 ltr/min. Figure 6.6 shows the graph drawn for the comparison of cooling capacities. It is clear that, for unit temperature difference the cooling capacity of supercritical oxygen is more than that of supercritical nitrogen and supercritical argon. Hence, it can be said that supercritical oxygen would be a better contender in terms of cooling capacity for a cryogenic cooling system.

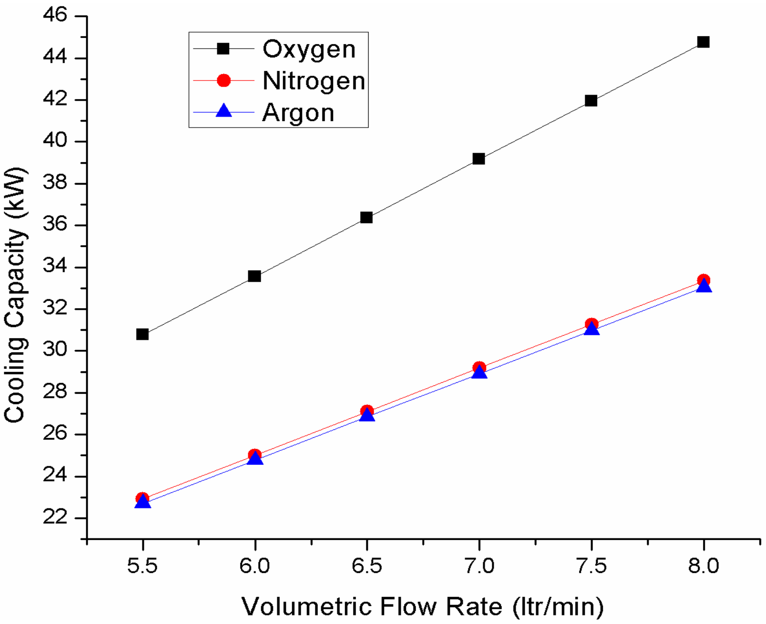

Figure 6.6 Cooling capacity comparison of different supercritical fluids

6.3 Analysis of cooling pipe of HTS Motor

A cooling pipe of HTS motor was designed and analysis was done on it by using COMSOL Multiphysics v3.5. It was design with the dimension of 25mm diameter and 250mm length. Oxygen was chosen as the operating fluid from material library and initial temperature and pressure was given to be 154.58 K and 5.043 MPa respectively. The load was given in the form of temperature at the cooling pipe walls. As superconductivity is possible upto the temperature of 133 K at ambient pressure, so it was necessary to assume a proper value for the temperature load. Lower limit of temperature was taken to be 160 K, as this value is around 5.5 K more than the working temperature of the fluid. Various fluid velocities were taken to find out the optimum value of velocity for maximum heat transfer. Optimum value was found to be 0.2m/s. While working at this velocity the free stream temperature was found to be minimum, which means maximum amount of heat, would be taken by the fluid at this velocity.

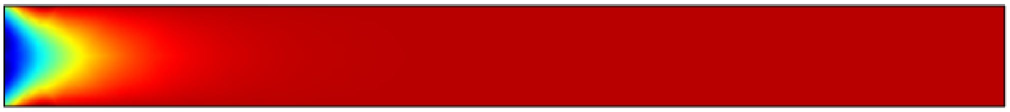

Figure 6.7 Flow of supercritical oxygen at v=0.001

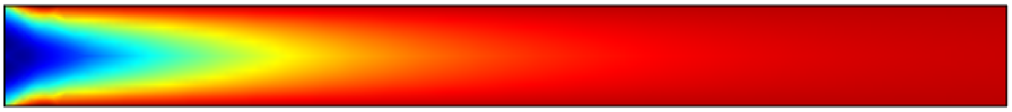

Figure 6.8 Flow of supercritical oxygen at v=0.005

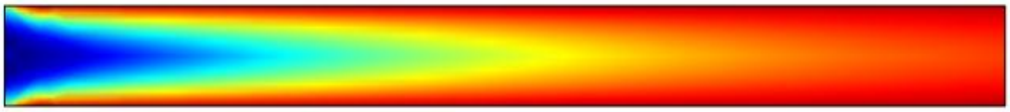

Figure 6.9 Flow of supercritical oxygen at v=0.01

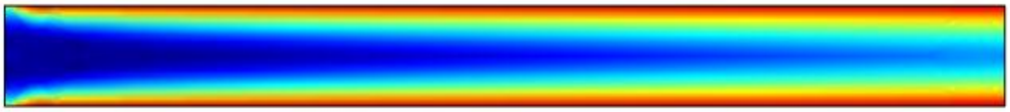

Figure 6.10 Flow of supercritical oxygen at v=0.05

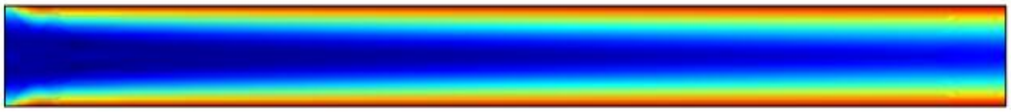

Figure 6.11 Flow of supercritical oxygen at v=0.1

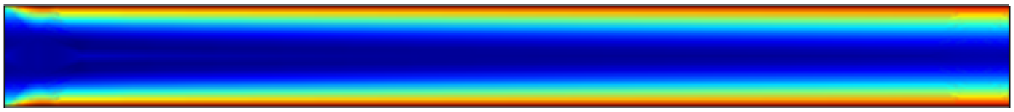

Figure 6.12 Flow of supercritical oxygen at v=0.2

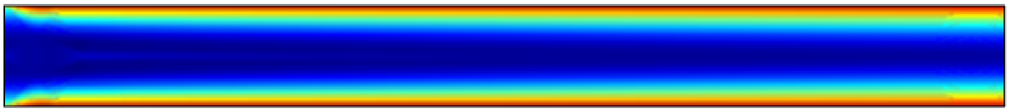

Figure 6.13 Flow of supercritical oxygen at v=0.25

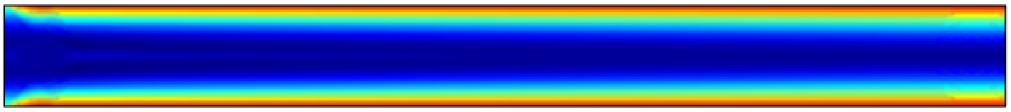

Figure 6.14 Flow of supercritical oxygen at v=0.3

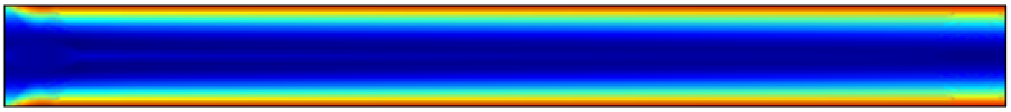

Figure 6.15 Flow of supercritical oxygen at v=0.5

Table VI Temperature at center at different velocities

Fluid Velocity	Temperature at the centre
0.001	159.9979
0.005	159.2189
0.01	157.796
0.05	154.826
0.1	154.369
0.2	154.29
0.25	154.309
0.3	154.33

0.5	154.4

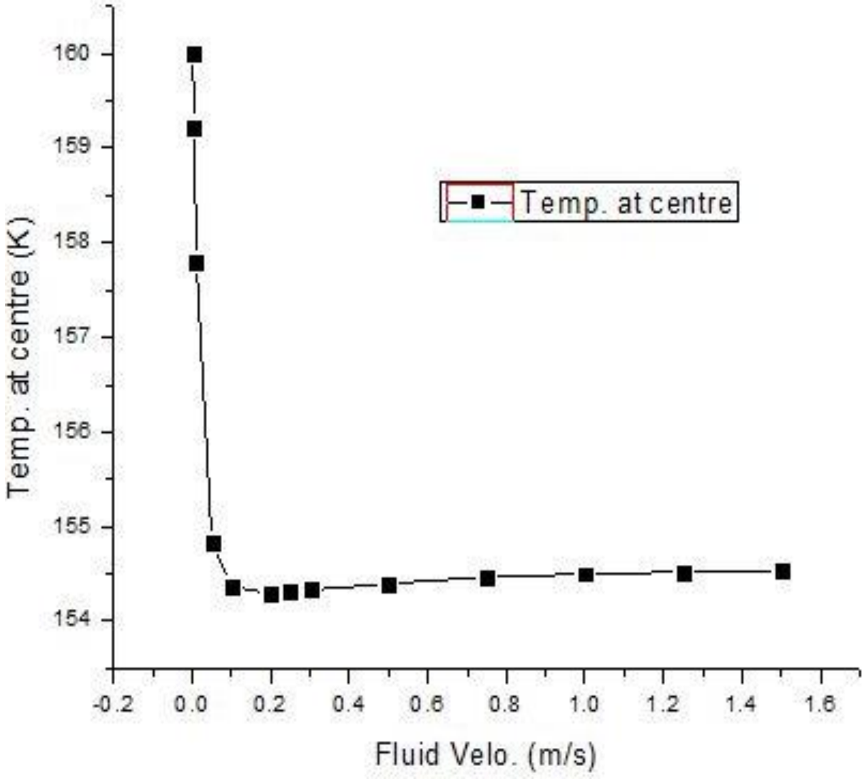

Figure 6.16 Center temperature vs Fluid Velocity

7 Conclusion

From the research work, it can be conclude that the developed correlations can be used for the estimation of the thermophysical properties. Moreover, they can even be used for the heat transfer analysis of various superconducting devices.

Due to higher supercritical temperature, it would require lesser energy to extract from oxygen to reach supercritical stage. Moreover, it was found that for the unit temperature difference, cooling capacity of Supercritical Oxygen (at supercritical point) is better as compared to that of Supercritical Nitrogen and Supercritical Argon. This means, use of Supercritical Oxygen would be beneficial for cooling purposes.

While using Supercritical Oxygen in the cooling pipe of HTS Motors, it was found that there is increase in convective heat transfer to the fluid and after a particular value of 0.2m/s heat transfer again decreases.

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Appendix

Thermophysical Properties of Supercritical Oxygen

Temperature (K)	Pressure (MPa)	Density (kg/m³)	Specific Heat (kJ/kg-K)	Therm. Cond. (W/m-K)	Viscosity (Pa-s)
154.58	5.043	466.41	719.48	0.10442	3.38E-05
154.68	5.043	339.76	46.849	0.05117	2.50E-05
154.78	5.043	323.44	28.453	0.04567	2.40E-05
154.88	5.043	312.82	21.317	0.04272	2.34E-05
154.98	5.043	304.77	17.395	0.04075	2.30E-05
155.08	5.043	298.22	14.873	0.03927	2.26E-05
155.18	5.043	292.68	13.097	0.0381	2.23E-05
155.28	5.043	287.85	11.769	0.03713	2.21E-05
155.38	5.043	283.56	10.734	0.03631	2.18E-05
155.48	5.043	279.69	9.9011	0.0356	2.16E-05
155.58	5.043	276.17	9.2144	0.03498	2.15E-05
155.68	5.043	272.93	8.6371	0.03443	2.13E-05
155.78	5.043	269.93	8.1441	0.03393	2.11E-05
155.88	5.043	267.13	7.7176	0.03348	2.10E-05
155.98	5.043	264.51	7.3443	0.03307	2.09E-05
156.08	5.043	262.04	7.0146	0.03269	2.08E-05
156.18	5.043	259.71	6.7209	0.03234	2.06E-05
156.28	5.043	257.5	6.4575	0.03201	2.05E-05
156.38	5.043	255.39	6.2196	0.03171	2.04E-05
156.48	5.043	253.38	6.0037	0.03143	2.03E-05
156.58	5.043	251.46	5.8066	0.03116	2.03E-05
156.68	5.043	249.63	5.6259	0.03091	2.02E-05
156.78	5.043	247.86	5.4596	0.03067	2.01E-05
156.88	5.043	246.16	5.3059	0.03045	2.00E-05
156.98	5.043	244.53	5.1634	0.03024	1.99E-05
157.08	5.043	242.95	5.0309	0.03004	1.99E-05
157.18	5.043	241.43	4.9073	0.02984	1.98E-05
157.28	5.043	239.95	4.7917	0.02966	1.97E-05
157.38	5.043	238.53	4.6834	0.02949	1.97E-05
157.48	5.043	237.14	4.5815	0.02932	1.96E-05

157.58	5.043	235.8	4.4857	0.02916	1.96E-05
157.68	5.043	234.49	4.3952	0.02901	1.95E-05
157.78	5.043	233.23	4.3097	0.02886	1.94E-05
157.88	5.043	231.99	4.2287	0.02872	1.94E-05
157.98	5.043	230.79	4.1519	0.02858	1.93E-05
158.08	5.043	229.62	4.0789	0.02845	1.93E-05
158.18	5.043	228.47	4.0095	0.02832	1.92E-05
158.28	5.043	227.36	3.9434	0.0282	1.92E-05
158.38	5.043	226.27	3.8803	0.02808	1.92E-05
158.48	5.043	225.2	3.8201	0.02796	1.91E-05
158.58	5.043	224.16	3.7625	0.02785	1.91E-05
158.68	5.043	223.15	3.7073	0.02774	1.90E-05
158.78	5.043	222.15	3.6545	0.02764	1.90E-05
158.88	5.043	221.17	3.6038	0.02754	1.89E-05
158.98	5.043	220.22	3.5551	0.02744	1.89E-05
159.08	5.043	219.28	3.5084	0.02735	1.89E-05
159.18	5.043	218.36	3.4634	0.02725	1.88E-05
159.28	5.043	217.46	3.4201	0.02717	1.88E-05
159.38	5.043	216.58	3.3784	0.02708	1.88E-05
159.48	5.043	215.71	3.3381	0.02699	1.87E-05
159.58	5.043	214.86	3.2993	0.02691	1.87E-05
159.68	5.043	214.02	3.2619	0.02683	1.87E-05
159.78	5.043	213.2	3.2256	0.02675	1.86E-05
159.88	5.043	212.39	3.1906	0.02667	1.86E-05
159.98	5.043	211.59	3.1567	0.0266	1.86E-05
160.08	5.043	210.81	3.1239	0.02653	1.85E-05
160.18	5.043	210.04	3.0922	0.02646	1.85E-05
160.28	5.043	209.28	3.0614	0.02639	1.85E-05
160.38	5.043	208.54	3.0315	0.02632	1.85E-05
160.48	5.043	207.81	3.0026	0.02625	1.84E-05
160.58	5.043	207.08	2.9744	0.02619	1.84E-05
160.68	5.043	206.37	2.9471	0.02612	1.84E-05
160.78	5.043	205.67	2.9206	0.02606	1.84E-05
160.88	5.043	204.98	2.8948	0.026	1.83E-05
160.98	5.043	204.3	2.8697	0.02594	1.83E-05
161.08	5.043	203.62	2.8453	0.02588	1.83E-05
161.18	5.043	202.96	2.8215	0.02583	1.83E-05
161.28	5.043	202.31	2.7983	0.02577	1.82E-05
161.38	5.043	201.66	2.7758	0.02572	1.82E-05
161.48	5.043	201.03	2.7538	0.02567	1.82E-05
161.58	5.043	200.4	2.7324	0.02561	1.82E-05
161.68	5.043	199.78	2.7115	0.02556	1.82E-05
161.78	5.043	199.16	2.6911	0.02551	1.81E-05

161.88	5.043	198.56	2.6712	0.02546	1.81E-05
161.98	5.043	197.96	2.6518	0.02542	1.81E-05
162.08	5.043	197.37	2.6328	0.02537	1.81E-05
162.18	5.043	196.79	2.6143	0.02532	1.81E-05
162.28	5.043	196.22	2.5962	0.02528	1.80E-05
162.38	5.043	195.65	2.5785	0.02523	1.80E-05
162.48	5.043	195.08	2.5612	0.02519	1.80E-05
162.58	5.043	194.53	2.5442	0.02514	1.80E-05
162.68	5.043	193.98	2.5277	0.0251	1.80E-05
162.78	5.043	193.44	2.5114	0.02506	1.80E-05
162.88	5.043	192.9	2.4956	0.02502	1.79E-05
162.98	5.043	192.37	2.48	0.02498	1.79E-05
163.08	5.043	191.84	2.4648	0.02494	1.79E-05
163.18	5.043	191.32	2.4499	0.0249	1.79E-05
163.28	5.043	190.81	2.4353	0.02486	1.79E-05
163.38	5.043	190.3	2.421	0.02483	1.79E-05
163.48	5.043	189.8	2.4069	0.02479	1.78E-05
163.58	5.043	189.3	2.3932	0.02475	1.78E-05
163.68	5.043	188.81	2.3797	0.02472	1.78E-05
163.78	5.043	188.32	2.3664	0.02468	1.78E-05
163.88	5.043	187.83	2.3534	0.02465	1.78E-05
163.98	5.043	187.36	2.3407	0.02461	1.78E-05
164.08	5.043	186.88	2.3282	0.02458	1.78E-05
164.18	5.043	186.41	2.3159	0.02455	1.77E-05
164.28	5.043	185.95	2.3038	0.02452	1.77E-05
164.38	5.043	185.49	2.292	0.02448	1.77E-05
164.48	5.043	185.03	2.2803	0.02445	1.77E-05
164.58	5.043	184.58	2.2689	0.02442	1.77E-05
164.68	5.043	184.13	2.2576	0.02439	1.77E-05
164.78	5.043	183.69	2.2466	0.02436	1.77E-05
164.88	5.043	183.25	2.2357	0.02433	1.77E-05
164.98	5.043	182.82	2.2251	0.0243	1.76E-05
165.08	5.043	182.38	2.2146	0.02428	1.76E-05
165.18	5.043	181.96	2.2042	0.02425	1.76E-05
165.28	5.043	181.53	2.1941	0.02422	1.76E-05
165.38	5.043	181.11	2.1841	0.02419	1.76E-05
165.48	5.043	180.7	2.1742	0.02417	1.76E-05
165.58	5.043	180.28	2.1646	0.02414	1.76E-05
165.68	5.043	179.87	2.155	0.02411	1.76E-05
165.78	5.043	179.47	2.1457	0.02409	1.76E-05
165.88	5.043	179.07	2.1364	0.02406	1.75E-05
165.98	5.043	178.67	2.1273	0.02404	1.75E-05
166.08	5.043	178.27	2.1184	0.02401	1.75E-05

166.18	5.043	177.88	2.1096	0.02399	1.75E-05
166.28	5.043	177.49	2.1009	0.02397	1.75E-05
166.38	5.043	177.1	2.0923	0.02394	1.75E-05
166.48	5.043	176.72	2.0839	0.02392	1.75E-05
166.58	5.043	176.34	2.0756	0.0239	1.75E-05
166.68	5.043	175.96	2.0674	0.02387	1.75E-05
166.78	5.043	175.59	2.0593	0.02385	1.75E-05
166.88	5.043	175.22	2.0513	0.02383	1.74E-05
166.98	5.043	174.85	2.0435	0.02381	1.74E-05
167.08	5.043	174.48	2.0358	0.02379	1.74E-05
167.18	5.043	174.12	2.0281	0.02377	1.74E-05
167.28	5.043	173.76	2.0206	0.02374	1.74E-05
167.38	5.043	173.4	2.0132	0.02372	1.74E-05
167.48	5.043	173.05	2.0058	0.0237	1.74E-05
167.58	5.043	172.69	1.9986	0.02368	1.74E-05
167.68	5.043	172.34	1.9915	0.02366	1.74E-05
167.78	5.043	172	1.9845	0.02364	1.74E-05
167.88	5.043	171.65	1.9775	0.02363	1.74E-05
167.98	5.043	171.31	1.9707	0.02361	1.74E-05
168.08	5.043	170.97	1.9639	0.02359	1.74E-05
168.18	5.043	170.63	1.9572	0.02357	1.73E-05
168.28	5.043	170.3	1.9506	0.02355	1.73E-05
168.38	5.043	169.96	1.9441	0.02353	1.73E-05
168.48	5.043	169.63	1.9377	0.02352	1.73E-05
168.58	5.043	169.3	1.9313	0.0235	1.73E-05
168.68	5.043	168.98	1.9251	0.02348	1.73E-05
168.78	5.043	168.66	1.9189	0.02346	1.73E-05
168.88	5.043	168.33	1.9128	0.02345	1.73E-05
168.98	5.043	168.01	1.9067	0.02343	1.73E-05
169.08	5.043	167.7	1.9007	0.02341	1.73E-05
169.18	5.043	167.38	1.8948	0.0234	1.73E-05
169.28	5.043	167.07	1.889	0.02338	1.73E-05
169.38	5.043	166.76	1.8833	0.02337	1.73E-05
169.48	5.043	166.45	1.8776	0.02335	1.73E-05
169.58	5.043	166.14	1.8719	0.02334	1.73E-05
169.68	5.043	165.84	1.8664	0.02332	1.72E-05
169.78	5.043	165.53	1.8609	0.02331	1.72E-05
169.88	5.043	165.23	1.8554	0.02329	1.72E-05
169.98	5.043	164.93	1.8501	0.02328	1.72E-05
170.08	5.043	164.64	1.8447	0.02326	1.72E-05
170.18	5.043	164.34	1.8395	0.02325	1.72E-05
170.28	5.043	164.05	1.8343	0.02323	1.72E-05
170.38	5.043	163.75	1.8292	0.02322	1.72E-05

170.48	5.043	163.46	1.8241	0.02321	1.72E-05
170.58	5.043	163.18	1.819	0.02319	1.72E-05
170.68	5.043	162.89	1.8141	0.02318	1.72E-05
170.78	5.043	162.6	1.8091	0.02317	1.72E-05
170.88	5.043	162.32	1.8043	0.02315	1.72E-05
170.98	5.043	162.04	1.7995	0.02314	1.72E-05
171.08	5.043	161.76	1.7947	0.02313	1.72E-05
171.18	5.043	161.48	1.79	0.02312	1.72E-05
171.28	5.043	161.2	1.7853	0.0231	1.72E-05
171.38	5.043	160.93	1.7807	0.02309	1.72E-05
171.48	5.043	160.66	1.7761	0.02308	1.72E-05
171.58	5.043	160.38	1.7716	0.02307	1.72E-05
171.68	5.043	160.11	1.7671	0.02306	1.71E-05
171.78	5.043	159.84	1.7627	0.02305	1.71E-05
171.88	5.043	159.58	1.7583	0.02303	1.71E-05
171.98	5.043	159.31	1.754	0.02302	1.71E-05
172.08	5.043	159.05	1.7497	0.02301	1.71E-05
172.18	5.043	158.78	1.7454	0.023	1.71E-05
172.28	5.043	158.52	1.7412	0.02299	1.71E-05
172.38	5.043	158.26	1.737	0.02298	1.71E-05
172.48	5.043	158	1.7329	0.02297	1.71E-05
172.58	5.043	157.75	1.7288	0.02296	1.71E-05
172.68	5.043	157.49	1.7247	0.02295	1.71E-05
172.78	5.043	157.24	1.7207	0.02294	1.71E-05
172.88	5.043	156.98	1.7167	0.02293	1.71E-05
172.98	5.043	156.73	1.7128	0.02292	1.71E-05
173.08	5.043	156.48	1.7089	0.02291	1.71E-05
173.18	5.043	156.23	1.705	0.0229	1.71E-05
173.28	5.043	155.99	1.7012	0.02289	1.71E-05
173.38	5.043	155.74	1.6974	0.02288	1.71E-05
173.48	5.043	155.5	1.6936	0.02287	1.71E-05
173.58	5.043	155.25	1.6899	0.02286	1.71E-05
173.68	5.043	155.01	1.6862	0.02285	1.71E-05
173.78	5.043	154.77	1.6826	0.02284	1.71E-05
173.88	5.043	154.53	1.6789	0.02284	1.71E-05
173.98	5.043	154.29	1.6754	0.02283	1.71E-05
174.08	5.043	154.05	1.6718	0.02282	1.71E-05
174.18	5.043	153.82	1.6683	0.02281	1.71E-05
174.28	5.043	153.58	1.6648	0.0228	1.71E-05
174.38	5.043	153.35	1.6613	0.02279	1.71E-05
174.48	5.043	153.11	1.6579	0.02278	1.71E-05
174.58	5.043	152.88	1.6545	0.02278	1.71E-05
174.68	5.043	152.65	1.6511	0.02277	1.70E-05

174.78	5.043	152.42	1.6477	0.02276	1.70E-05
174.88	5.043	152.19	1.6444	0.02275	1.70E-05
174.98	5.043	151.97	1.6411	0.02275	1.70E-05
175.08	5.043	151.74	1.6379	0.02274	1.70E-05
175.18	5.043	151.52	1.6346	0.02273	1.70E-05
175.28	5.043	151.29	1.6314	0.02272	1.70E-05
175.38	5.043	151.07	1.6283	0.02272	1.70E-05
175.48	5.043	150.85	1.6251	0.02271	1.70E-05
175.58	5.043	150.63	1.622	0.0227	1.70E-05
175.68	5.043	150.41	1.6189	0.0227	1.70E-05
175.78	5.043	150.19	1.6158	0.02269	1.70E-05
175.88	5.043	149.97	1.6128	0.02268	1.70E-05
175.98	5.043	149.75	1.6097	0.02267	1.70E-05
176.08	5.043	149.54	1.6067	0.02267	1.70E-05
176.18	5.043	149.32	1.6038	0.02266	1.70E-05
176.28	5.043	149.11	1.6008	0.02266	1.70E-05
176.38	5.043	148.9	1.5979	0.02265	1.70E-05
176.48	5.043	148.69	1.595	0.02264	1.70E-05
176.58	5.043	148.48	1.5921	0.02264	1.70E-05
176.68	5.043	148.27	1.5892	0.02263	1.70E-05
176.78	5.043	148.06	1.5864	0.02262	1.70E-05
176.88	5.043	147.85	1.5836	0.02262	1.70E-05
176.98	5.043	147.64	1.5808	0.02261	1.70E-05
177.08	5.043	147.44	1.578	0.02261	1.70E-05
177.18	5.043	147.23	1.5753	0.0226	1.70E-05
177.28	5.043	147.03	1.5725	0.0226	1.70E-05
177.38	5.043	146.82	1.5698	0.02259	1.70E-05
177.48	5.043	146.62	1.5672	0.02259	1.70E-05
177.58	5.043	146.42	1.5645	0.02258	1.70E-05
177.68	5.043	146.22	1.5618	0.02258	1.70E-05
177.78	5.043	146.02	1.5592	0.02257	1.70E-05
177.88	5.043	145.82	1.5566	0.02256	1.70E-05
177.98	5.043	145.62	1.554	0.02256	1.70E-05
178.08	5.043	145.43	1.5515	0.02255	1.70E-05
178.18	5.043	145.23	1.5489	0.02255	1.70E-05
178.28	5.043	145.03	1.5464	0.02254	1.70E-05
178.38	5.043	144.84	1.5439	0.02254	1.70E-05
178.48	5.043	144.65	1.5414	0.02253	1.70E-05
178.58	5.043	144.45	1.5389	0.02253	1.70E-05
178.68	5.043	144.26	1.5365	0.02253	1.70E-05
178.78	5.043	144.07	1.534	0.02252	1.70E-05
178.88	5.043	143.88	1.5316	0.02252	1.70E-05
178.98	5.043	143.69	1.5292	0.02251	1.70E-05

179.08	5.043	143.5	1.5268	0.02251	1.70E-05
179.18	5.043	143.31	1.5245	0.02251	1.70E-05
179.28	5.043	143.12	1.5221	0.0225	1.70E-05
179.38	5.043	142.94	1.5198	0.0225	1.70E-05
179.48	5.043	142.75	1.5175	0.02249	1.70E-05
179.58	5.043	142.57	1.5152	0.02249	1.70E-05
179.68	5.043	142.38	1.5129	0.02249	1.70E-05
179.78	5.043	142.2	1.5106	0.02248	1.70E-05
179.88	5.043	142.01	1.5083	0.02248	1.70E-05
179.98	5.043	141.83	1.5061	0.02247	1.70E-05
180.08	5.043	141.65	1.5039	0.02247	1.70E-05
180.18	5.043	141.47	1.5017	0.02247	1.70E-05
180.28	5.043	141.29	1.4995	0.02246	1.70E-05
180.38	5.043	141.11	1.4973	0.02246	1.70E-05
180.48	5.043	140.93	1.4952	0.02246	1.70E-05
180.58	5.043	140.75	1.493	0.02245	1.70E-05
180.68	5.043	140.58	1.4909	0.02245	1.70E-05
180.78	5.043	140.4	1.4888	0.02245	1.70E-05
180.88	5.043	140.22	1.4867	0.02244	1.70E-05
180.98	5.043	140.05	1.4846	0.02244	1.70E-05
181.08	5.043	139.87	1.4825	0.02244	1.70E-05
181.18	5.043	139.7	1.4804	0.02244	1.70E-05
181.28	5.043	139.53	1.4784	0.02243	1.70E-05
181.38	5.043	139.35	1.4764	0.02243	1.70E-05
181.48	5.043	139.18	1.4743	0.02243	1.70E-05
181.58	5.043	139.01	1.4723	0.02242	1.70E-05
181.68	5.043	138.84	1.4703	0.02242	1.70E-05
181.78	5.043	138.67	1.4683	0.02242	1.70E-05
181.88	5.043	138.5	1.4664	0.02242	1.70E-05
181.98	5.043	138.33	1.4644	0.02241	1.70E-05
182.08	5.043	138.16	1.4625	0.02241	1.70E-05
182.18	5.043	138	1.4606	0.02241	1.70E-05
182.28	5.043	137.83	1.4586	0.02241	1.70E-05
182.38	5.043	137.66	1.4567	0.02241	1.70E-05
182.48	5.043	137.5	1.4548	0.0224	1.70E-05
182.58	5.043	137.33	1.453	0.0224	1.70E-05
182.68	5.043	137.17	1.4511	0.0224	1.70E-05
182.78	5.043	137	1.4492	0.0224	1.70E-05
182.88	5.043	136.84	1.4474	0.02239	1.70E-05
182.98	5.043	136.68	1.4455	0.02239	1.70E-05
183.08	5.043	136.52	1.4437	0.02239	1.70E-05
183.18	5.043	136.36	1.4419	0.02239	1.70E-05
183.28	5.043	136.19	1.4401	0.02239	1.70E-05

183.38	5.043	136.03	1.4383	0.02238	1.70E-05
183.48	5.043	135.87	1.4365	0.02238	1.70E-05
183.58	5.043	135.72	1.4348	0.02238	1.70E-05
183.68	5.043	135.56	1.433	0.02238	1.70E-05
183.78	5.043	135.4	1.4313	0.02238	1.70E-05
183.88	5.043	135.24	1.4295	0.02238	1.70E-05
183.98	5.043	135.08	1.4278	0.02237	1.70E-05
184.08	5.043	134.93	1.4261	0.02237	1.70E-05
184.18	5.043	134.77	1.4244	0.02237	1.70E-05
184.28	5.043	134.62	1.4227	0.02237	1.70E-05
184.38	5.043	134.46	1.421	0.02237	1.70E-05
184.48	5.043	134.31	1.4193	0.02237	1.70E-05
184.58	5.043	134.15	1.4177	0.02237	1.70E-05
184.68	5.043	134	1.416	0.02236	1.70E-05
184.78	5.043	133.85	1.4144	0.02236	1.70E-05
184.88	5.043	133.7	1.4127	0.02236	1.70E-05
184.98	5.043	133.54	1.4111	0.02236	1.70E-05
185.08	5.043	133.39	1.4095	0.02236	1.70E-05
185.18	5.043	133.24	1.4079	0.02236	1.70E-05
185.28	5.043	133.09	1.4063	0.02236	1.70E-05
185.38	5.043	132.94	1.4047	0.02236	1.70E-05
185.48	5.043	132.79	1.4031	0.02236	1.70E-05
185.58	5.043	132.65	1.4016	0.02236	1.70E-05
185.68	5.043	132.5	1.4	0.02236	1.70E-05
185.78	5.043	132.35	1.3985	0.02236	1.70E-05
185.88	5.043	132.2	1.3969	0.02235	1.70E-05
185.98	5.043	132.06	1.3954	0.02235	1.70E-05
186.08	5.043	131.91	1.3939	0.02235	1.70E-05
186.18	5.043	131.76	1.3923	0.02235	1.70E-05
186.28	5.043	131.62	1.3908	0.02235	1.70E-05
186.38	5.043	131.47	1.3893	0.02235	1.70E-05
186.48	5.043	131.33	1.3879	0.02235	1.70E-05
186.58	5.043	131.19	1.3864	0.02235	1.70E-05
186.68	5.043	131.04	1.3849	0.02235	1.70E-05
186.78	5.043	130.9	1.3834	0.02235	1.70E-05
186.88	5.043	130.76	1.382	0.02235	1.70E-05
186.98	5.043	130.62	1.3805	0.02235	1.70E-05
187.08	5.043	130.47	1.3791	0.02235	1.70E-05
187.18	5.043	130.33	1.3777	0.02235	1.70E-05
187.28	5.043	130.19	1.3762	0.02235	1.70E-05
187.38	5.043	130.05	1.3748	0.02235	1.70E-05
187.48	5.043	129.91	1.3734	0.02235	1.70E-05
187.58	5.043	129.77	1.372	0.02235	1.70E-05

187.68	5.043	129.63	1.3706	0.02235	1.70E-05
187.78	5.043	129.5	1.3692	0.02235	1.70E-05
187.88	5.043	129.36	1.3678	0.02235	1.70E-05
187.98	5.043	129.22	1.3665	0.02235	1.70E-05
188.08	5.043	129.08	1.3651	0.02235	1.70E-05
188.18	5.043	128.95	1.3638	0.02235	1.70E-05
188.28	5.043	128.81	1.3624	0.02235	1.70E-05
188.38	5.043	128.67	1.3611	0.02235	1.70E-05
188.48	5.043	128.54	1.3597	0.02235	1.70E-05
188.58	5.043	128.4	1.3584	0.02235	1.70E-05
188.68	5.043	128.27	1.3571	0.02235	1.70E-05
188.78	5.043	128.14	1.3558	0.02235	1.70E-05
188.88	5.043	128	1.3545	0.02235	1.70E-05
188.98	5.043	127.87	1.3532	0.02235	1.70E-05
189.08	5.043	127.74	1.3519	0.02235	1.71E-05
189.18	5.043	127.6	1.3506	0.02235	1.71E-05
189.28	5.043	127.47	1.3493	0.02235	1.71E-05
189.38	5.043	127.34	1.348	0.02235	1.71E-05
189.48	5.043	127.21	1.3468	0.02235	1.71E-05
189.58	5.043	127.08	1.3455	0.02235	1.71E-05
189.68	5.043	126.95	1.3442	0.02235	1.71E-05
189.78	5.043	126.82	1.343	0.02235	1.71E-05
189.88	5.043	126.69	1.3418	0.02236	1.71E-05
189.98	5.043	126.56	1.3405	0.02236	1.71E-05
190.08	5.043	126.43	1.3393	0.02236	1.71E-05
190.18	5.043	126.3	1.3381	0.02236	1.71E-05
190.28	5.043	126.17	1.3369	0.02236	1.71E-05
190.38	5.043	126.04	1.3357	0.02236	1.71E-05
190.48	5.043	125.92	1.3345	0.02236	1.71E-05
190.58	5.043	125.79	1.3333	0.02236	1.71E-05
190.68	5.043	125.66	1.3321	0.02236	1.71E-05
190.78	5.043	125.54	1.3309	0.02236	1.71E-05
190.88	5.043	125.41	1.3297	0.02236	1.71E-05
190.98	5.043	125.28	1.3285	0.02236	1.71E-05
191.08	5.043	125.16	1.3274	0.02236	1.71E-05
191.18	5.043	125.03	1.3262	0.02237	1.71E-05
191.28	5.043	124.91	1.325	0.02237	1.71E-05
191.38	5.043	124.78	1.3239	0.02237	1.71E-05
191.48	5.043	124.66	1.3228	0.02237	1.71E-05
191.58	5.043	124.54	1.3216	0.02237	1.71E-05
191.68	5.043	124.41	1.3205	0.02237	1.71E-05
191.78	5.043	124.29	1.3194	0.02237	1.71E-05
191.88	5.043	124.17	1.3182	0.02237	1.71E-05

191.98	5.043	124.05	1.3171	0.02237	1.71E-05
192.08	5.043	123.92	1.316	0.02238	1.71E-05
192.18	5.043	123.8	1.3149	0.02238	1.71E-05
192.28	5.043	123.68	1.3138	0.02238	1.71E-05
192.38	5.043	123.56	1.3127	0.02238	1.71E-05
192.48	5.043	123.44	1.3116	0.02238	1.71E-05
192.58	5.043	123.32	1.3105	0.02238	1.71E-05
192.68	5.043	123.2	1.3095	0.02238	1.71E-05
192.78	5.043	123.08	1.3084	0.02238	1.71E-05
192.88	5.043	122.96	1.3073	0.02239	1.71E-05
192.98	5.043	122.84	1.3062	0.02239	1.71E-05
193.08	5.043	122.73	1.3052	0.02239	1.71E-05
193.18	5.043	122.61	1.3041	0.02239	1.71E-05
193.28	5.043	122.49	1.3031	0.02239	1.71E-05
193.38	5.043	122.37	1.302	0.02239	1.71E-05
193.48	5.043	122.25	1.301	0.0224	1.71E-05
193.58	5.043	122.14	1.3	0.0224	1.71E-05
193.68	5.043	122.02	1.2989	0.0224	1.71E-05
193.78	5.043	121.91	1.2979	0.0224	1.71E-05
193.88	5.043	121.79	1.2969	0.0224	1.71E-05
193.98	5.043	121.67	1.2959	0.0224	1.71E-05
194.08	5.043	121.56	1.2949	0.02241	1.72E-05
194.18	5.043	121.44	1.2939	0.02241	1.72E-05
194.28	5.043	121.33	1.2929	0.02241	1.72E-05
194.38	5.043	121.21	1.2919	0.02241	1.72E-05
194.48	5.043	121.1	1.2909	0.02241	1.72E-05
194.58	5.043	120.99	1.2899	0.02242	1.72E-05
194.68	5.043	120.87	1.2889	0.02242	1.72E-05
194.78	5.043	120.76	1.2879	0.02242	1.72E-05
194.88	5.043	120.65	1.287	0.02242	1.72E-05
194.98	5.043	120.53	1.286	0.02242	1.72E-05
195.08	5.043	120.42	1.285	0.02243	1.72E-05
195.18	5.043	120.31	1.2841	0.02243	1.72E-05
195.28	5.043	120.2	1.2831	0.02243	1.72E-05
195.38	5.043	120.09	1.2822	0.02243	1.72E-05
195.48	5.043	119.98	1.2812	0.02243	1.72E-05
195.58	5.043	119.87	1.2803	0.02244	1.72E-05
195.68	5.043	119.75	1.2793	0.02244	1.72E-05
195.78	5.043	119.64	1.2784	0.02244	1.72E-05
195.88	5.043	119.53	1.2775	0.02244	1.72E-05
195.98	5.043	119.43	1.2766	0.02244	1.72E-05
196.08	5.043	119.32	1.2756	0.02245	1.72E-05
196.18	5.043	119.21	1.2747	0.02245	1.72E-05

196.28	5.043	119.1	1.2738	0.02245	1.72E-05
196.38	5.043	118.99	1.2729	0.02245	1.72E-05
196.48	5.043	118.88	1.272	0.02245	1.72E-05
196.58	5.043	118.77	1.2711	0.02246	1.72E-05
196.68	5.043	118.67	1.2702	0.02246	1.72E-05
196.78	5.043	118.56	1.2693	0.02246	1.72E-05
196.88	5.043	118.45	1.2684	0.02246	1.72E-05
196.98	5.043	118.34	1.2675	0.02247	1.72E-05
197.08	5.043	118.24	1.2666	0.02247	1.72E-05
197.18	5.043	118.13	1.2658	0.02247	1.72E-05
197.28	5.043	118.02	1.2649	0.02247	1.72E-05
197.38	5.043	117.92	1.264	0.02247	1.72E-05
197.48	5.043	117.81	1.2632	0.02248	1.72E-05
197.58	5.043	117.71	1.2623	0.02248	1.72E-05
197.68	5.043	117.6	1.2614	0.02248	1.72E-05
197.78	5.043	117.5	1.2606	0.02249	1.72E-05
197.88	5.043	117.39	1.2597	0.02249	1.72E-05
197.98	5.043	117.29	1.2589	0.02249	1.73E-05
198.08	5.043	117.19	1.258	0.02249	1.73E-05
198.18	5.043	117.08	1.2572	0.0225	1.73E-05
198.28	5.043	116.98	1.2564	0.0225	1.73E-05
198.38	5.043	116.87	1.2555	0.0225	1.73E-05
198.48	5.043	116.77	1.2547	0.0225	1.73E-05
198.58	5.043	116.67	1.2539	0.02251	1.73E-05
198.68	5.043	116.57	1.253	0.02251	1.73E-05
198.78	5.043	116.46	1.2522	0.02251	1.73E-05
198.88	5.043	116.36	1.2514	0.02251	1.73E-05
198.98	5.043	116.26	1.2506	0.02252	1.73E-05
199.08	5.043	116.16	1.2498	0.02252	1.73E-05
199.18	5.043	116.06	1.249	0.02252	1.73E-05
199.28	5.043	115.96	1.2482	0.02253	1.73E-05
199.38	5.043	115.86	1.2474	0.02253	1.73E-05
199.48	5.043	115.76	1.2466	0.02253	1.73E-05
199.58	5.043	115.66	1.2458	0.02253	1.73E-05
199.68	5.043	115.55	1.245	0.02254	1.73E-05
199.78	5.043	115.46	1.2442	0.02254	1.73E-05
199.88	5.043	115.36	1.2434	0.02254	1.73E-05
199.98	5.043	115.26	1.2427	0.02254	1.73E-05
200.08	5.043	115.16	1.2419	0.02255	1.73E-05
200.18	5.043	115.06	1.2411	0.02255	1.73E-05
200.28	5.043	114.96	1.2403	0.02255	1.73E-05
200.38	5.043	114.86	1.2396	0.02256	1.73E-05
200.48	5.043	114.76	1.2388	0.02256	1.73E-05

200.58	5.043	114.67	1.238	0.02256	1.73E-05
200.68	5.043	114.57	1.2373	0.02257	1.73E-05
200.78	5.043	114.47	1.2365	0.02257	1.73E-05
200.88	5.043	114.37	1.2358	0.02257	1.73E-05
200.98	5.043	114.28	1.235	0.02257	1.73E-05
201.08	5.043	114.18	1.2343	0.02258	1.73E-05
201.18	5.043	114.08	1.2336	0.02258	1.73E-05
201.28	5.043	113.99	1.2328	0.02258	1.73E-05
201.38	5.043	113.89	1.2321	0.02259	1.74E-05
201.48	5.043	113.79	1.2313	0.02259	1.74E-05
201.58	5.043	113.7	1.2306	0.02259	1.74E-05
201.68	5.043	113.6	1.2299	0.0226	1.74E-05
201.78	5.043	113.51	1.2292	0.0226	1.74E-05
201.88	5.043	113.41	1.2284	0.0226	1.74E-05
201.98	5.043	113.32	1.2277	0.02261	1.74E-05
202.08	5.043	113.22	1.227	0.02261	1.74E-05
202.18	5.043	113.13	1.2263	0.02261	1.74E-05
202.28	5.043	113.03	1.2256	0.02262	1.74E-05
202.38	5.043	112.94	1.2249	0.02262	1.74E-05
202.48	5.043	112.85	1.2242	0.02262	1.74E-05
202.58	5.043	112.75	1.2235	0.02262	1.74E-05
202.68	5.043	112.66	1.2228	0.02263	1.74E-05
202.78	5.043	112.57	1.2221	0.02263	1.74E-05
202.88	5.043	112.47	1.2214	0.02263	1.74E-05
202.98	5.043	112.38	1.2207	0.02264	1.74E-05
203.08	5.043	112.29	1.22	0.02264	1.74E-05
203.18	5.043	112.2	1.2193	0.02264	1.74E-05
203.28	5.043	112.1	1.2186	0.02265	1.74E-05
203.38	5.043	112.01	1.218	0.02265	1.74E-05
203.48	5.043	111.92	1.2173	0.02266	1.74E-05
203.58	5.043	111.83	1.2166	0.02266	1.74E-05
203.68	5.043	111.74	1.2159	0.02266	1.74E-05
203.78	5.043	111.65	1.2153	0.02267	1.74E-05
203.88	5.043	111.56	1.2146	0.02267	1.74E-05
203.98	5.043	111.47	1.2139	0.02267	1.74E-05
204.08	5.043	111.37	1.2133	0.02268	1.74E-05
204.18	5.043	111.28	1.2126	0.02268	1.74E-05
204.28	5.043	111.19	1.212	0.02268	1.74E-05
204.38	5.043	111.1	1.2113	0.02269	1.74E-05
204.48	5.043	111.01	1.2106	0.02269	1.74E-05
204.58	5.043	110.93	1.21	0.02269	1.75E-05