Development of correlations for Thermophysical properties of Supercritical Nitrogen(SCN) to be used in High Temperature Superconducting(HTS) Cables

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Abstract

Future power transmission applications demand higher energy efficiency. In order to conserve the transmission of electrical energy is a new challenge. At present, transmission of electrical energy with conventional electrical cables reported to have 40-60% losses. In order to overcome such critical challenges, a novel method of transmission is being developed using High Temperature Superconducting (HTS) cables. However, cooling of HTS cables need appropriate cryogenic coolant which can remove the deposited or infiltrated heat loads on the superconducting tapes. In the present work, Supercritical nitrogen (SCN) is proposed as one such cryogen which can be used in HTS cables due to its peculiar thermophysical properties such as density, viscosity, thermal conductivity and specific heat.

As the nitrogen is the major constituent in the atmospheric air, the concern over its availability may not arise. Thereby, it can be separated from air and can be converted in to SCN using various cryocoolers. In this proposed work, a conceptual application of SCN in HTS cables is introduced. Moreover various thermophysical (thermodynamic and transport) properties of SCN were studied in order to investigate the feasibility with HTS cables. Further, the variation of thermophysical properties with respect to temperature (T_c + 50K) and pressure (P_c + 10bar) were analyzed. The analyzed results show that for every 0.1K rise in temperature, there is drastic variation in thermophysical properties. Moreover, correlations have been developed for different thermophysical properties at critical pressure (P_c=33.958bar) and for different temperatures (up to T_c+50K) of SCN. The obtained correlations of SCN can be used for predicting thermohydraulic performance of futuristic HTS cables.

Introduction

High Temperature Superconducting (HTS) cables experience technological challenges in efficient cooling. The cooling requirements need estimation of AC losses in the superconductors [1-8], pressure drop and parasitic heat loads [9-12]. Hence, in this regard various cooling strategies were proposed in the past [13-15] and numerical investigation on flow behavior of LN2 was done [16-19]. However, all the strategies discussed till date involve multiphase flows of which modelling and experimentation turned out to be a great challenge.

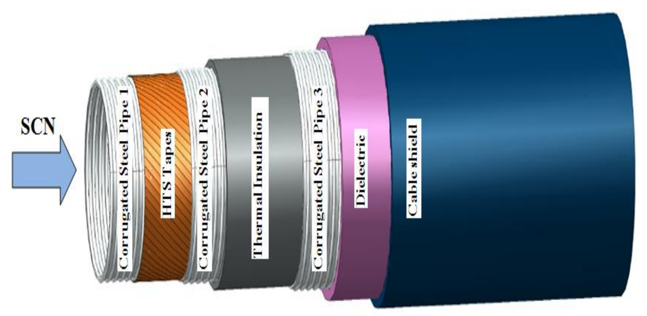

Fig. 1. Geometry of HTS coaxial cable with different insulations modelled using ABAQUS

In this paper, cooling of HTS cables with Supercritical Nitrogen (SCN) is proposed. The critical temperature and pressure of SCN is found to be 126.19K and 33.958bar respectively [20]. Moreover, thermophysical properties such as density, viscosity, thermal conductivity and specific heat of SCN, due to their unique behavior, were studied over a wide range of temperatures and pressures. In future, there is a scope of developing room temperature superconducting cables which can be cooled by SCN.

Development of Correlations

- Correlations have been developed in order to estimate the variation of thermophysical properties with respect to temperature (T_c+50K) at critical pressure. These correlations were developed with the assumption that there is no significant change in the properties beyond T_c+50K in the supercritical region. Further, the developed correlations may be useful while thermal modelling of HTS cables.
- Correlation expressions were chosen of rational type because of its simplicity and less number of correlation coefficients. Moreover, it explains the relationship between dependent and independent variables. The difference between the magnitude of thermophysical properties at critical temperature and critical pressure is significantly larger than those above the critical temperature. In this event, critical temperature (T_c) of SCN was not considered for fitting. A Total of 500 data points has been taken from NIST [20] and analyzed.

Table I: Thermophysical Properties at Critical Temperature and Pressure (P_c=33.958 bar)

Critical Temperature (K)	Thermophysical Properties			
	Density (kg/m³)	Viscosity (Pa-s)	Thermal conductivity (W/m-K)	Specific Heat (kJ/kg-K)
126.19	342.67	2.0645E-5	0.13472	729.99

Table II: Developed correlations and their coefficients for Thermophysical Properties at various Temperature Range

PROPERTIES	TEMPERATURE RANGE	CORRELATION	COEFFICIENTS	R^2- VALUE
Density	126.29K≤T<127.99K	$\rho(T)=\frac{\rho_2+\rho_3*T}{1+\rho_1*T}$	$\rho_1=-0.00797, \rho_2=148.8154, \rho_3=-1.19116$	0.99789
	128.09K<T<135.89K	$\rho(T)=\frac{\rho_5+\rho_6*T}{1+\rho_4*T}$	$\rho_4=0.00829, \rho_5=74.63959, \rho_6=-0.66828$	0.99984
	135.99K<T≤176.19K	$\rho(T)=\frac{\rho_8+\rho_9*T}{1+\rho_7*T}$	$\rho_7=-0.00962, \rho_8=2.99702, \rho_9=-0.30743$	0.99987
Viscosity	126.29K≤T<127.99K	$\mu(T)=\frac{\mu_2+\mu_3*T}{1+\mu_1*T}$	$\mu_1=-0.00796, \mu_2=1.19E-05, \mu_3=-9.47E-08$	0.99818
	128.09K<T<135.89K	$\mu(T)=\frac{\mu_5+\mu_6*T}{1+\mu_4*T}$	$\mu_4=-0.008, \mu_5=1.12E-05, \mu_6=-8.99E-08$	0.99971
	135.99K<T≤176.19K	$\mu(T)=\mu_7+\mu_8*T^1+\mu_9*T^2+\mu_{10}*T^3$	$\mu_7=8.38E-05, \mu_8=-1.36E-06, \mu_9=8.40E-09, \mu_{10}=-1.67E-11$	0.99969
Specific Heat	126.29K≤T<127.99K	$c_P(T)=\frac{c_{P2}+c_{P3}*T}{1+c_{P1}*T}$	$c_{p1}=-0.00793, c_{p2}=3.18982, c_{p3}=-0.02567$	0.99956
	128.09K<T≤176.19K	$c_P(T)=\frac{c_{P5}+c_{P6}*T}{1+c_{P4}*T}$	$c_{p4}=-0.00799, c_{p5}=0.941, c_{p6}=-0.00843$	0.99958
Thermal conductivity	126.29K≤T<127.99K	$\kappa(T)=\frac{1+\kappa_3*T}{\kappa_1+\kappa_2*T}$	$\kappa_1=-0.00794, \kappa_2=0.02496, \kappa_3=-1.99E-04$	0.99708
	128.09K<T<145.99K	$\kappa(T)=\frac{\kappa_5+\kappa_6*T}{1+\kappa_4*T}$	$\kappa_4=-0.00803, \kappa_5=0.01626, \kappa_6=-1.34E-04$	0.99962
	146.09K<T≤176.19K	$\kappa(T)=\kappa_7+\kappa_8*T^1+\kappa_9*T^2+\kappa_{10}*T^3$	$\kappa_7=0.24416, \kappa_8=-0.00402, \kappa_9=2.37E-05, \kappa_{10}=-4.59E-08$	0.99957

Error Estimation Analysis

- In order to ascertain the quality of the developed correlations, statistical parameters has been used. Small values of parameters refer to dependable correlation. The Arithmetic Average of the Absolute Values of the Relative Errors (AARE %) is defined in Eq. (1) is an indication of the accuracy of correlation. Another parameter is defined as Sum of Absolute of Residual (SAR) which is defined in Eq. (2), shows the reliability of correlation for more dense data points.

$$AARE\% = \frac{100}{N}\sum_{i=1}^{500}\left(\left|\frac{X^{act}-X^{cal}}{X^{act}}\right|\right).....(1) \qquad SAR = \sum_{i=1}^{500}\left|X^{act}-X^{cal}\right|....(2)$$

- The Average Percent Relative Error (ARE %), which is defined in Eq. (3), gives a measure of the bias of the correlation; a value of zero indicates a random of the measured values around the correlation. Fig. 6 shows Percent Relative Error (RE %) which is defined in Eq. (4) for each thermophysical properties correlation as a function of temperature.

$$ARE\% = \frac{100}{N}\sum_{i=1}^{500}\left(\frac{X^{act}-X^{cal}}{X^{act}}\right).....(3) \qquad RE\% = 100\times\left(\frac{X^{act}-X^{cal}}{X^{act}}\right)....(4)$$

- Moreover, increasing in temperature causes decrease in relative error for the correlations developed.

Table III: Statistical value for each thermophysical properties at P_c=33.958 bar

Properties	AARE%	ARE%	SAR
Density	0.2820	-0.0290	188.7149
Viscosity	0.4330	-3.79E-01	2.704E-05
Specific heat	1.0673	0.1680	32.4109
Thermal Conductivity	0.5858	1.04E-01	0.07282

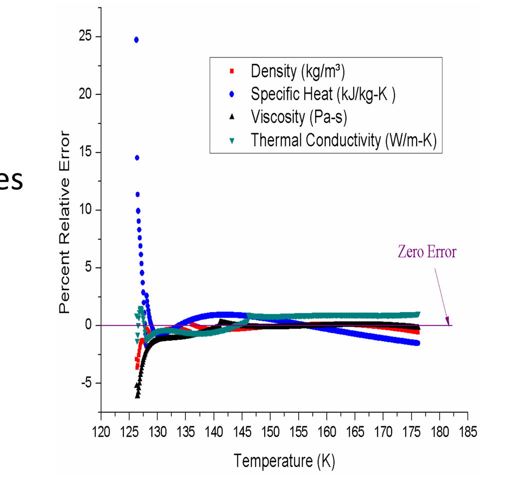

Fig.6 Percent Relative Error as function of Temperature

Conclusion

Application of Supercritical Nitrogen (SCN) in HTS cables is explored in the present work. Moreover, thermophysical properties of SCN such as Density, Viscosity, Thermal Conductivity and Specific Heat were studied. In addition, correlations are developed which accurately fit to the standard database available with NIST. The scope of the development of the correlations is extendable for various cryogenic applications in future.

Study of Thermophysical Properties of SCN

- Liquid nitrogen, due to its cryogenic nature and good heat carrying capacity is being used in cryogenic applications. In this paper, the thermophysical properties of SCN have been studied at and above the critical point. Moreover, correlations for density, viscosity, thermal conductivity and specific heat have been developed at critical pressure (P_c=33.958bar) over a wide range of temperatures (T_c+50K). These correlations can be beneficial for prediction of pressure drop and heat transfer in HTS cables.
- Initially, thermophysical properties were observed at constant pressure with varying temperatures. Number of data points (500 points) were obtained from NIST-REFPROP [20] with in the pressure range of 33.958bar to 43.958bar. Plots were drawn and discussed in the following sections.
- Above Figures reveals, the behavior of thermophysical properties of SCN as a function of temperature at various pressures. Moreover, it is observed that as temperature increases (126.19K-176.19K) the density, thermal conductivity, specific heat decreases while viscosity increases. This may be due to, at higher temperature the molecules move further apart as their Kinetic Energy increases with increase in temperature.
- Also, it is observed that as pressure increases (P_c+10bar) the specific heat, thermal conductivity, viscosity, density increases. This may be due to, the movement of SCN molecules moving closer to each other with increase in pressure. In addition, it is observed that there is a drastic change in thermophysical properties for every 0.1K rise in temperature.
- Above the critical temperature, in the temperature range 126.19K<T>145K, density and viscosity of SCN are observed to be decreasing which signifies, the pumping power of SCN in HTS cables can be reduced. And also it can be observed that, specific heat of SCN is increasing in the temperature range 126.29K<T>140K which signifies, at this particular temperatures, SCN can absorb more amount of heat which is generated inside the HTS cable. In addition, beyond this temperature range, constant specific heat is observed.
- And also, thermal conductivity of SCN is getting increased beyond 163.49K which signifies that, more amount of heat can be extracted by SCN.

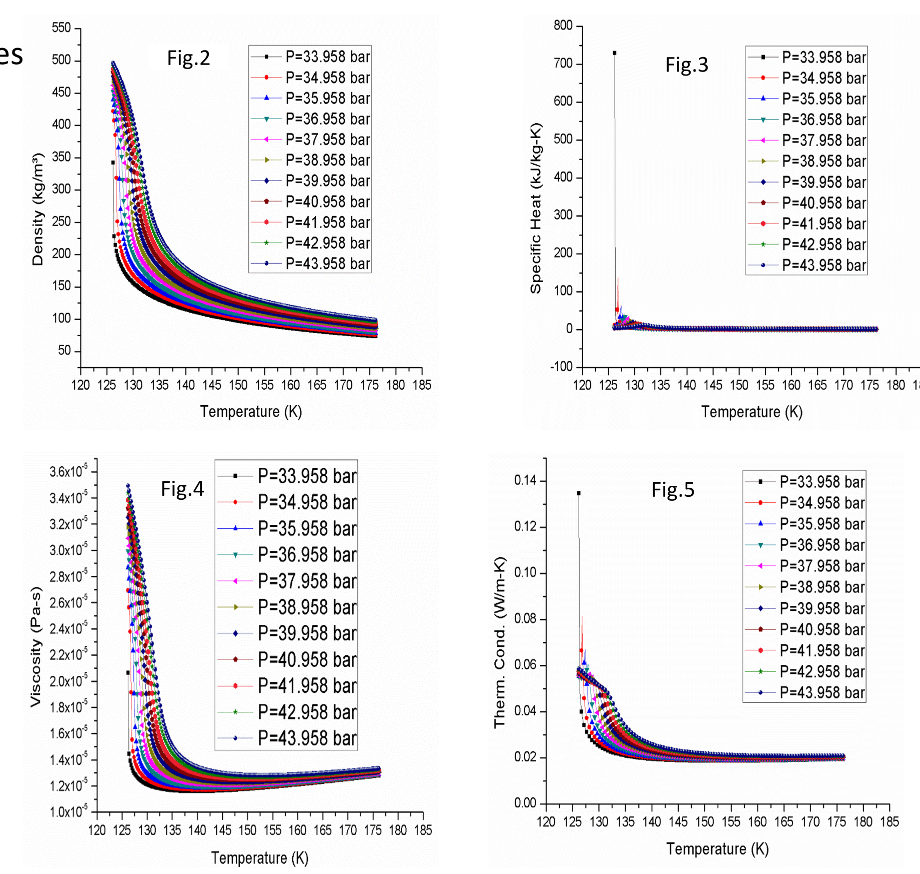

Fig.2 to Fig. 5 Shows thermophysical Properties as a function of Temperature at various Pressures

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