Feasibility Analysis on Cryogenic Properties of Supercritical Nitrogen to be used in the Cooling of Hg-Based High Temperature Superconductors for Electric Aircraft Propulsion

Abhinav Kumar, J. V. Muruga Lal Jeyan

Abstract: ***Electrified Aircraft Propulsion (EAP) and Advanced Hybrid Electric Aircrafts (AHEA) like NASA NX-3, SUGAR, NASA X-57 and STARC ABL are going to be the future of avionics as they have potential to improve fuel economy, emissions and noise levels. The agencies have suggested using superconducting cables for the electric transmission to reduce heat losses. The limit of critical current has reached 134 K where Hg- based ceramic materials are available that can superconduct at this temperature range. In order to retain the superconductivity, the cables have to be cooled below its critical temperature. Liquid nitrogen (LN2) boils of at 77 K which further leads to multiphase heat transfer challenges. An attempt has been made in the present work to overcome such challenges and a novel concept of using Supercritical Nitrogen (SCN), having critical temperature 126.19K and pressure as 3.3958MPa (consist single phase), as a cryogen for the cooling of Hg-Based Superconductors, has been introduced. Drastic variations have been found for thermophysical properties of SCN near the critical point. It has been concluded that few temperature and pressure ranges are suitable if one wants to incorporate SCN as cryogen for Hg-based superconductors.***

Keywords: ***Electrified Aircraft Propulsion, Supercritical Nitrogen, Hg-Based Superconductors, Superconducting cables, Supercritical Fluids, Hybrid Electric Aircrafts.***

I. INTRODUCTION

This Electrical Aircrafts are destined to be the future of aviation and propulsion systems as they can provide better outcomes with respect to response time, durability, emissions, safety and economic viability than currently available aviation systems. Recently, a concept of hybrid aircrafts has been widely introduced by the aviation communities as they have to meet the pollution norms imposed by the parent governmental agencies. It includes the contribution of both conventional jet engines technology and novel electric aircraft systems where electrical power can be used in take-off, climbing and landing of the aircraft as it only contributes to 25% of the total power consumption. In order to reduce the losses during transmission, use of superconducting cables have been suggested by various researchers [1-5]. As superconducting cables are more efficient than conventional copper cables, thus the former can be used in power transmission from the gas turbine unit to the tail fan used for Boundary Layer Ingesting (BLI) such as in STARC ABL hybrid electric aircraft (Fig. 1).

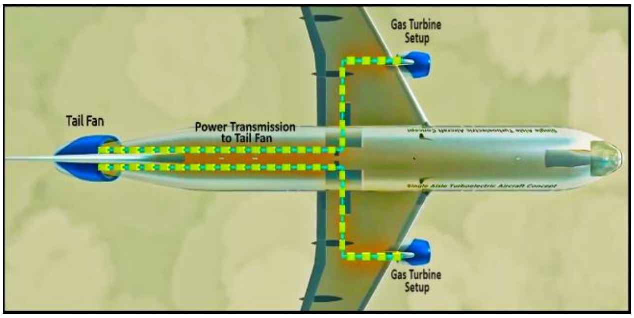

Figure 1. Schematic of STARC ABL hybrid electric aircraft

High temperature superconductors (HTS) are one of eligible contender which have been exploited in various applications such as energy storage [6]-[8], proficient power transmission (transformers or cables) [9]-[11], ship propulsion using motors [12]-[15], power generation (Generators) [16]-[18], and magnetic levitating trains [19][20]. To maintain superconductivity, there is a need to dissipate the heat load generated due to AC losses imposed on the superconducting tape [21]-[23]. These heating loads are required to compensate by an efficient cooling system which may be conduction or convection cooled. In the literature, various studies have been performed where different strategies have been proposed in order to acquire efficient cooling [24][25]. Numerical models have been also intended in order to simulate the LN2 flow behavior [26]-[29]. Few researchers have proposed supercritical cryogens as a novel cryogen due to its astonishing properties in order to achieve efficient cooling [25].

At present, the highest superconducting temperature that can be achieved for HTS is found to be 134K and further attempts have been made to expand this bound. However, in order to sustain the superconducting nature of such HTSs, efficient cooling is required. In this context, it is important to invent novel techniques for the efficient cooling of Hg- Based HTSs by avoiding complexity related with multi-phase physics.

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Therefore, in this study an attempt has been made in introducing a novel cryogen, Supercritical Nitrogen (SCN) having single phase, for the efficient cooling of Hg-Based HTSs. SCN is a fluid coming into existence when it is being pressurized at and above the critical pressure (3.3958MPa) and heated to a temperature greater than equal to critical temperature (126.19K). It consists liquid like densities and vapor like diffusivities with zero surface tension. At and above critical conditions (Pc and Tc), distinct phase does not exist and interface between liquid and vapor phase disappears.

In the present manuscript, thermophysical properties have been studied which would help in the computational analysis of Hg-Based HTSs used to transmit AC or DC current in electric aircrafts. After analyzing the variations, few temperature ranges have been suggested which would help in achieving the efficient cooling of HTSs. Also, in order to use such properties for the computational studies related to the cooling of Hg-based superconducting tape or cable, a correlation has been developed through simple curve fitting as a function of both temperature and pressure for the SCN. It has been concluded that the correlated properties match excellently with the NIST Database [30].

II. PROPERTIES OF SUPERCRITICAL NITROGEN

NIST Database has been used to acquire the thermophysical properties of SCN [31]. In order to observe the property variations, the data has been extracted at and above the critical pressure for large temperature range. To quantify the variation, curve fitting has been done for future use in the computational codes such as MATLAB/ANSYS.

A. SCN Property Variation

The properties of SCN have been plotted in 2-D for a various ranges of temperature (127-200K) and pressure (3.4 to 4MPa) in the supercritical regime. In the present manuscript, study has been done above critical temperature and pressure as it is not possible to work near critical point in practice as fluid can shift its phase to liquid or vapor depending on the extent of pressure drop during the flow.

Fig. 2 (a-f) shows the property variation in the SC regime and it can be seen from the plots that drastic variations have been experienced by all properties. From (a and b), it is very much clear that both density and viscosity experienced a drastic drop with respect to temperature for all pressures and both properties tending to increase with pressure in a isothermal process. Lower values are acceptable as it would help in reducing pumping power required for the cryogen to flow and pressure drop due to friction. From the plots, it can be noticed that it is better to use SCN between temperature ranges from 127-140K as within this range viscosity is minimum with appropriate density. Fig. 2 (c and e) shows the variation of specific heat and thermal conductivity in SC regime. From Fig. 1 (c), it is can be noticed that the variation in specific heat is large from Tc to 130K. It can also be observed that at lower pressures, pseudo-critical point has higher values and variation is found to be abrupt on the either side of this point. Moderate values of thermal conductivity have been found between a temperature limit varies from 127-140K shown in Fig. 2 (e). As the specific heat value of SCN is much higher than the liquid and gaseous phase of Nitrogen within 127-140K, thus high convective heat transfer rates can be achieved.

Fig. 2 (d and f) shows the variation of isothermal compressibility and volume expansivity as a function of temperature and pressure which indicate that density is a strong function of pressure and temperature respectively near the critical zone.

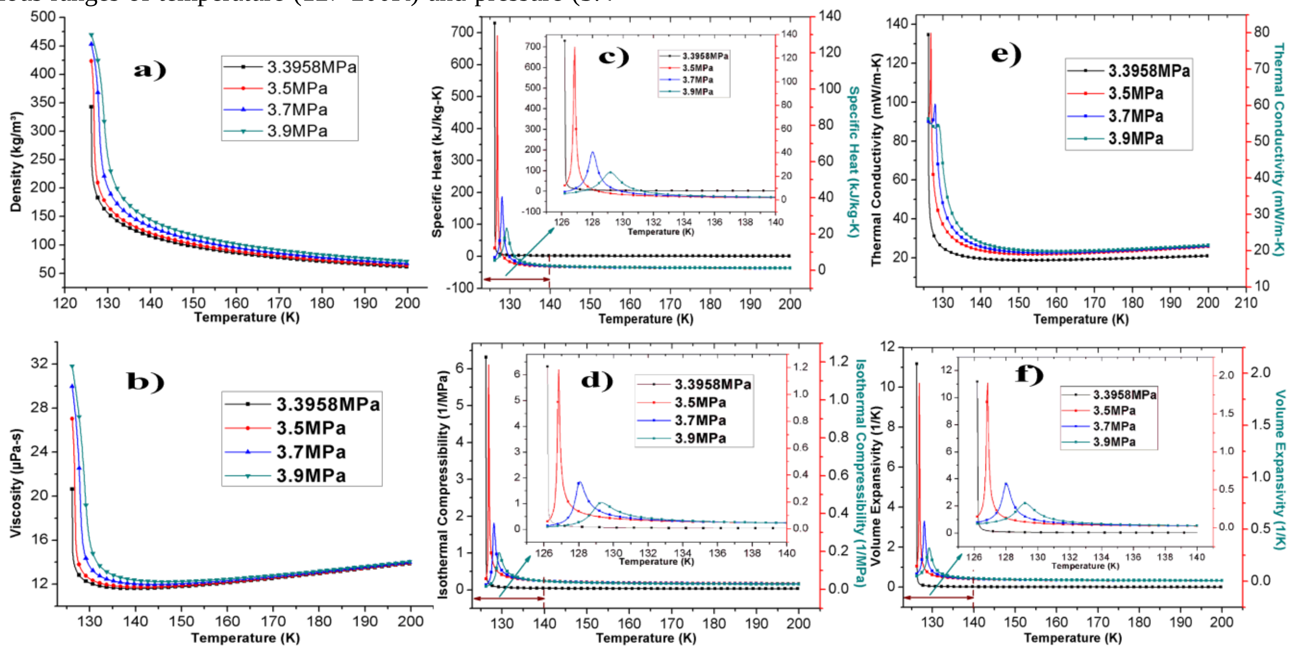

Fig. 2. Variation of Thermophysical Properties with respect to Temperatures at Various Pressures in Supercritical Regime.

As properties have considerably excellent values within 127-140K thus SCN (in a temperature range of 127-133K and pressure range varies from 3.4 to 3.7MPa) can be employed for the cooling of Hg-Based HTSs which has Tc=134K.

B. Development of Correlations

Fig. 2 shows the variation in properties with temperature and pressure. Drastic changes in all the properties have been observed near the supercritical region. In order to capture this variation, study has been done from 3.4MPa to 4MPa for density, 3.4MPa to 3.7MPa for specific heat, viscosity and thermal conductivity.

Table- I: Coefficients for the Properties.

Property	Density (25556 Data Points)	Thermal Conductivity (28804 Data Points)
Temperature Range	**3.4 to 4MPa & 127-200K**	**3.4 to 3.7MPa 128-200K**
p_0	-1488.88727	-67.1211
a_1	15.84905	0.84238
a_2	0.02428	0.04027
a_3	9.17951E-05	2.00016E-04
a_4	2.42961E-06	-7.94729E-07
b_1	-196.192	-12.9664
b_2	-27.5371	1.62166
b_3	14.14434	-0.21479
b_4	-5.4047	-3.69915
b_5	0.71559	0.43753
R^2 Value	**0.986**	**0.994**

Due to abrupt changes in properties curve fitting becomes bit complex using single correlation, consequently non-linear piecewise modeling has been performed to match the properties with NIST data with premier correctness and least error. In order to capture the variation in density, viscosity and thermal conductivity of SCN, a two statistical models have been employed successfully (1) and (2). The proposed statistical models show a great reliability while retracing the NIST property data.

$$(\rho, \mu, k) = \frac{p_0 + a_1 T + b_1 P + b_2 P^2 + b_3 P^3}{1 + a_2 T + a_3 T^2 + a_4 T^3 + b_4 P + b_5 P^2} \qquad (1)$$

$$(c_p) = a_2 + \frac{(a_1 - a_2)}{1 + \exp((T_0 - T)/p)} \qquad (2)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N} (f_i^{cal} - f_i^{nist})^2}{\sum_{i=1}^{N} (f_i^{cal} - f_i^{mean})^2} \qquad (3)$$

$$\text{where } f_i^{mean} = \frac{1}{N} \sum_{i=1}^{n} f^{cal}$$

Here ‘f’ represents the thermophysical property and Fig. 3 (R-1 and R-2) indicates the Percent Relative Error (PRE) which is found to higher at critical region and is increasing with pressures.

Where T is temperature in ‘K’, P is pressure in ‘MPa’ and all others are constants. As in the vicinity of the critical region, abrupt variations in almost all the properties have been found as shown in Fig. 2, thus, few temperature points have been excluded (1K for thermal conductivity and 2K for viscosity) while estimating the properties. Individual numbers of data points that have been used to generate correlation are mentioned in the Table I to Table III. The correlation coefficients for the density, thermal conductivity, viscosity and specific heat have been tabulated in Table I to Table III.

Table- II: Correlation Coefficients for Viscosity

Property	Viscosity (μPa-s) (28804 Data Points)			
	3.4 to 3.5MPa		**3.6 to 3.7MPa**	
Temperature Range	**128-142K**	**142.01-200K**	**128-142K**	**142.01-200K**
p_0	762.791	3.80427	109.65576	9.0723
a_1	11.42879	-0.06006	9.45769	-0.05278
a_2	2.33314	0.0053	1.41032	0.00494
a_3	0.01466	-7.875E-05	-3.75652E-04	-6.64554E-05
a_4	-9.41082E-05	1.76232E-07	-8.34311E-06	1.46159E-07
b_1	17.83937	5.87119	-46.23624	-1.98784
b_2	-51.10889	-1.16291	-29.84038	1.40265
b_3	-32.53264	0.13137	-14.11282	-0.16724
b_4	-51.19926	-0.21414	-17.54259	-0.3114
b_5	-11.67908	0.05704	-6.68614	0.05767
R^2 Value	**0.982**	**0.998**	**0.93**	**0.99**

Table- III: Correlation Coefficients for Specific Heat

Supercritical Nitrogen Properties		Temperature Range	Correlation Coefficients (Data Points- 3650 for each Pressure) a_1	a_2	T_0	p	R^2
Specific Heat (kJ/kg-K)	3.4MPa	127-130K	3.00408	14704.29636	116.34955	-0.31069	0.994
		130.02-135.02K	2.29128	38.53747	121.66651	-0.15705	
		135.04-200K	1.252	3893.20234	31.83819	-0.03389	
	3.5MPa	127-128.68K	7.12265	122902.034	124.39174	-1.3774	0.992
		128.7-135.7K	2.51906	2850.6984	114.04158	-0.19499	
		135.72-200K	1.24077	2440.77145	27.18957	-0.03044	
	3.6MPa	127-127.4K	17.09286	85.63548	127.32644	4.28621	0.996
		127.42-129.5K	7.04851	94554.39196	124.92884	-1.28388	
		129.52-139.52K	2.22709	5292.14693	109.41935	-0.15502	
		139.54-200K	1.22489	1265.92308	22.62809	-0.02671	
	3.7MPa	127-128K	10.15968	59.67453	127.87451	1.98172	0.997
		128.02-130.62K	5.83769	21961.49245	124.46884	-0.77958	
		130.64-140.64K	2.16046	3508.38269	108.94217	-0.13819	
		140.66-200K	1.22792	1183.78016	23.79446	-0.02651	

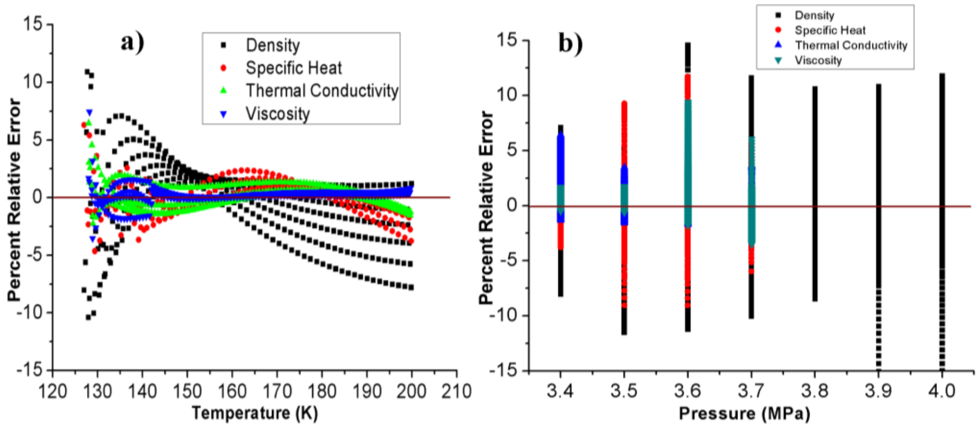

Fig. 3. Error Analysis for the Developed Correlations

Table- IV: AARE and SAR Values

SCN	Pressure Range		AARE (%)	SAR
Density	3.4 to 4MPa		2.51	79844
Thermal Conductivity	3.4 to 3.7MPa		0.74	4568
Viscosity	3.4 to 3.5MPa	128-142K	0.29	12.15
		142.01-200K	0.19	285
	3.6 to 3.7MPa	128-142K	1.62	582
		142.01-200K	0.35	534
Specific Heat	3.4MPa	127-200K	1.6	103
	3.5MPa		1.32	132
	3.6MPa		1.02	158
	3.7MPa		0.88	117

Therefore, these equations can be incorporated in the simulation packages via using user defined functions in order to capture the physics changing w.r.t. temperature and pressure. Different statistical factors like AARE (%) and SAR have been estimated and lower values (Table IV) show correctness of the fit [25]. R^2 Value is found to approximate equal to 1.

III. CONCLUSION

From the present study it has been concluded that SCN can be employed as a cryogen in order to sustain the superconductivity of Hg-Based High Temperature Superconductors for a temperature limit of 127-133K. As properties are considerably excellent within 127-140K thus SCN (in a temperature range of 127-133K and pressure range of 3.4 to 3.7MPa) can be employed for the cooling of Hg-Based HTSs used in electric aircraft applications which has Tc=134K. Moreover, developed correlations show good accuracy in estimating viscosity, thermal conductivity and specific heat. Near the critical point as density is a strong function of temperature and pressure thus large errors are associated in estimating its value near Tc and Pc as shown in Fig. 4 (a and b). Developed correlation can be implemented in the simulation software using user defined functions in order to capture precise physics related to flow and heat transfer characteristics.

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