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Numerical Model to Estimate the Thermophysical Properties of Oxygen at Critical Pressure to be used in SMES

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Abstract : *The development of High Temperature Superconductors (HTS) made a path for Superconducting Magnetic Energy Storage Systems (SMES) to emerge as a viable technology for high energy storage uses. Moreover, the essence for need of a dependable, fast, stable and flexible power compensation devices in the power production industries make the ideal opportunities for SMES. However, an active refrigeration system is required to keep these superconducting magnets at a very low temperature, to allow indefinite circulation of electrical energy in the superconducting magnetic loop. In the present work, a novel approach of cooling concept with oxygen at critical pressure region has been proposed to maintain the superconducting state of HTS magnet in SMES. Moreover, the thermophysical properties such as density, viscosity, specific heat and thermal conductivity have been studied over a wide range of temperatures (154.58K-204.58K) at critical pressure (P_c=50.43 bar). Also, the correlation for oxygen at critical pressure has been developed. These correlations can be used in prior prediction of SMES performance under various operating conditions and also improve the efficiency of SMES. Moreover, the SMES system can be possibly made smaller and cost effective.*

Keywords - *SMES, Pure Oxygen, Thermophysical Properties, Correlation*

I. INTRODUCTION

At present, renewable energy resources have become of particular interest, both in terms of alternate sources and steadiness in electrical power systems [1-3]. Moreover, dependency on renewable resource power has been growing due to its enormous accessibility and less harmful effects to the environment. However, the potential of these power sources frequently changes and are barely predictable, due to change in the climatic and environmental conditions. This may lead to unwanted complications in power distribution systems, due to severe fluctuations of tie-line power flow [4]. To overcome this problem, superconducting magnetic energy storage (SMES) can be developed as an active device, which have the ability to possess high storage efficiency, response fast and high cyclability, but these is only limited for short periods of time. [5].

Essentially, SMES includes three basic components: a superconducting magnet, a cryostat, and a power conditioning connection system to the load [6].The general components of the SMES unit are shown in Fig.1. In this study, the focus is emphasized on improving the efficiency of cryostat, because it helps in maintaining the superconducting state of the magnet.

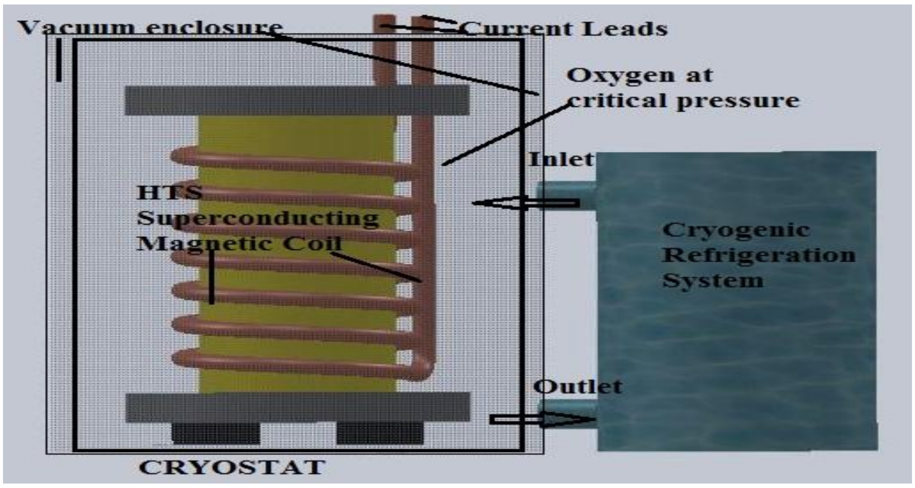

Fig 1: Conceptual 3-D Model of SMES with Oxygen at Critical pressure

SMES are cryogenic devices, whose temperature is required to be kept low to ensure non-dissipative operation of the HTS superconducting wires. The temperature is maintained with the help of cold source, which is used and generally fixed before the SMES coil design. The isolation of these coils cannot be done easily from outside, because there are heat losses due to radiation from the cryostat external surface, by conduction through the mechanical support of the coil and the current leads. Moreover, there are losses due to Joule effect in the current leads and networks between the superconducting wires. Also, the winding in coil also promotes heat generation during charging and discharging operations. As a result, an efficient thermal system must be designed to maintain the coil temperature low enough to allow safe operation. This cooling system must have the capability to efficiently absorb this heat flux generated, otherwise the temperature would slowly increase, which would progressively increase the heat dissipation and trigger a slow thermal runaway. This results in dissipation of energy in small volumes, also known as hot spots, where temperature rises rapidly. These might lead to thermal expansion, causing high mechanical stresses and possibly deformations to which HTS materials performances are highly vulnerable. There is also a possibility of melting of conductor links, when the temperature goes higher than the conductor's critical values. Therefore it is essential to have an effective cryogenic fluid in the cryostat to bind the hotspots at maximum temperature and the temperature gradients along the conductor, which requires an active protection [9-11].

Therefore, in this paper, we propose the use of cryogenic oxygen fluid, for cooling the superconducting magnetic coils. Also, we develop the numerical correlations for calculating the thermophysical properties of oxygen, which is valid for temperature range from 155.78 to 204.58 K at pressure 50.43bar. The primary aim of the work is to define the proper refrigeration system which is most suitable for integration into SMES magnet systems. Hence, propose a better way to improve the performance of power distribution systems

II. THERMOPHYSICAL PROPERTIES OF OXYGEN

During the charging and discharging process in SMES, a large amount of heat energy is produced in the coils. Therefore, there is a need to bind the thermal hotspots generated due to heating in the coil and to enhance the heat removal process. The higher removal rate of heat is necessary by cryogenic fluids to maintain the magnet in superconducting state [12-15]. However, this cryogenic fluid must have effective compatibility with the cryogenic refrigeration unit for better heat removal process with minimal refrigeration power. Also considering the ability of oxygen to quantify the heat content of a fluid or change in temperature of a fluid for an amount of heat generated, the specific gravity of fluid and mass transport property of oxygen is needed to be analyzed. Therefore, for the novel oxygen cryogenic fluid, density, specific heat, viscosity and thermal conductivity are the significant thermophysical properties which are being studied here with respect to variation in temperatures and pressures. The study of thermophysical properties is carried out on the assumption that the properties of oxygen depends on the spherical molecular configuration and inter-molecular interactions [9-11].

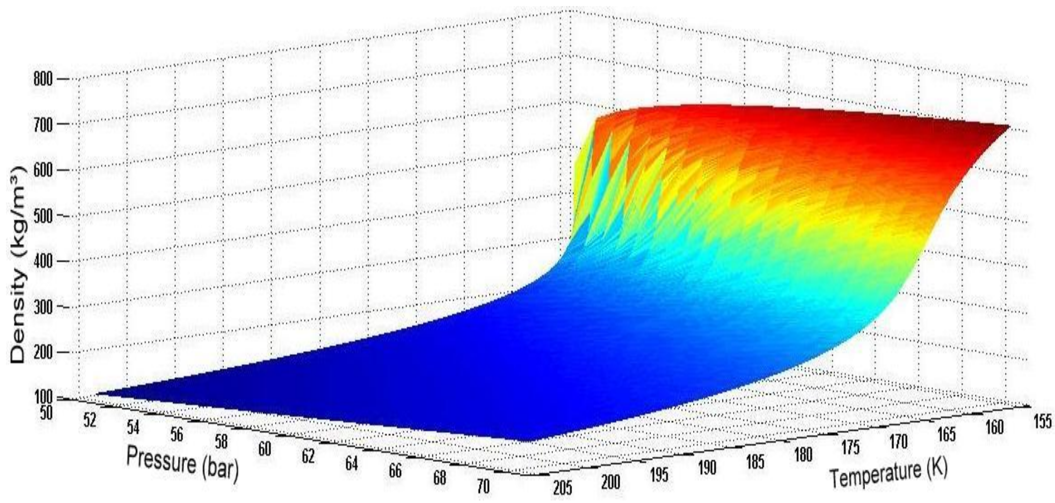

Fig 2: Variation of Density as a function of temperature (154.58K-204.58K) and Pressure (50.43bar-70.43bar)

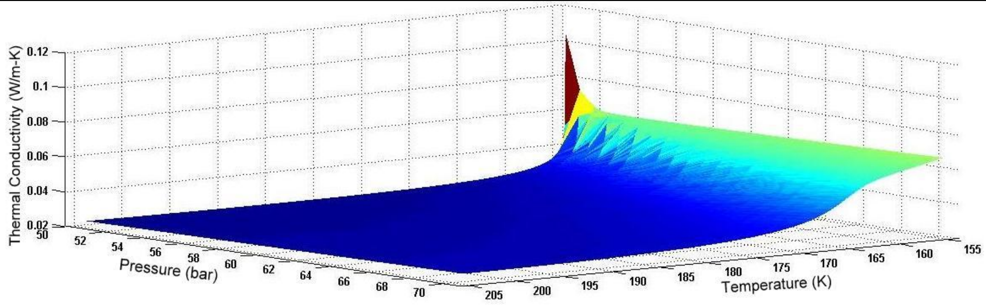

Fig 3: Variation of Thermal Conductivity as a function of temperature (154.58K-204.58K) and pressure(50.43bar-70.43bar)

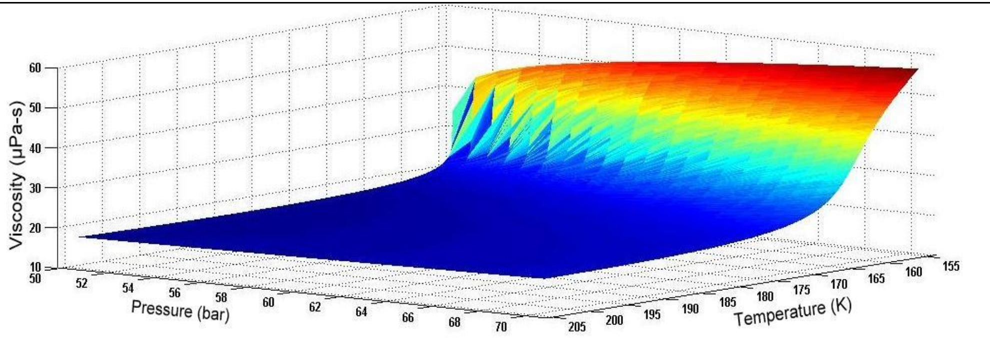

Fig 4: Variation of Viscosity as a function of temperature (154.58K-204.58K) and pressure(50.43bar-70.43bar)

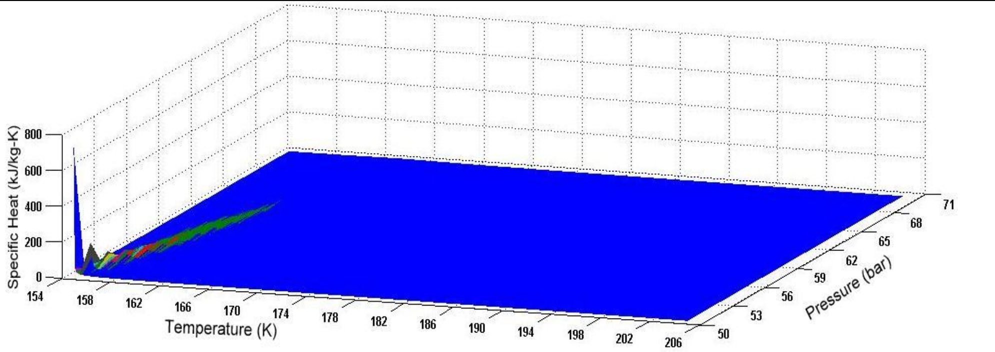

Fig 5: Variation of Specific heat as a function of temperature (154.58K-204.58K) and pressure(50.43bar-70.43bar)

Figure 2 illustrates the effect of temperature on density at different pressures. It is observed that the density is decreasing exponentially with increase in temperature (154.58K to 204.58K). But as the pressure increases from 50.43bar to 70.43bar, it is showing increasing phenomena. Similarly, in Figure 3, thermal conductivity illustrates an exponential decrease with respect to increase in temperature (154.58K to204.58K) and increase with pressure (50.43 to 70.43bar). However, in Figure 4 viscosity illustrates an exponential decay from 154.58K to 182.08K and logistic or sigmoidal growth in nature from 182.18K-204.58K. But, with increase in pressure, viscosity is increasing. Moreover, in Figure 5, the specific heat at constant pressure shows the development of pseudo critical points. But after these pseudo critical points, specific heat illustrates an exponential decay in nature with increase in temperature as well as with increase in pressure from 50.43bar to70.43bar. 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 (50.43 to 70.43bar) the thermal conductivity, viscosity, density increases. This may be due to, the movement of oxygen molecules; they tend to moving closer to each other with increase in pressure. In addition, it is observed that there is drastic changes in thermophysical properties for every 0.1K rise in temperature near the critical pressure and temperature.

III. DESCRIPTION OF CORRELATION

It has been observed above from the study of thermophysical properties that, density, specific heat, thermal conductivity of oxygen is decreasing exponentially with increase in temperature. However, viscosity doesn't show the same phenomena. Instead it decreases exponentially till 182.08K, thereafter from 182.18K-204.58K it shows a sigmoidal growth in curve. Therefore, Exponential decay and Boltzmann correlations have been developed to estimate the variation of thermophysical properties of oxygen with respect to temperature (T_C+50K) at critical pressure (P_c=50.43bar). Table I shows the various correlation and correlation coefficient values. Moreover, correlation expressions were chosen of Exponential decay and Boltzmann growth type because of its simplicity and less number of correlation coefficients. However, the difference between the magnitude of thermophysical properties of critical temperature and critical pressure is significantly larger than those near the critical temperature. In this event, critical temperature (T_C=154. 58K) and 154.68K of oxygen is not considered for fitting at critical pressure (Pc= 50.43bars). A total of 499 data points for each property has been taken from NIST [19] and used to develop the correlations.

Table 1: Developed correlations and their correlation coefficients for thermophysical properties of oxygen at critical pressure

Properties	Temperature Range	Correlation and Correlation Coefficients	Adj. R^2 value
Density (kg/m^3)	154.78K ≤ T ≤ 204.58 K	$\rho=\rho_0+\rho_1*e^{-\left(\frac{T-t_0}{t_1}\right)}+\rho_2*e^{-\left(\frac{T-t_0}{t_2}\right)}+\rho_3*e^{-\left(\frac{T-t_0}{t3}\right)}$ ρ_0 = 86.83795, ρ_1 = 44.37694, ρ_2 = 66.85646, ρ_3 = 126.30558 t_0 = 154.74508, t_1 = 0.62934, t_2 = 4.11627, t_3 = 30.34234	0.99997
Specific Heat (kJ/kg-K)	154.78K ≤ T ≤ 204.58 K	$\varsigma=\varsigma_0+\varsigma_1 e^{-\left(\frac{T-t_0}{t_1}\right)}+\varsigma_2 e^{-\left(\frac{T-t_0}{t_2}\right)}+\varsigma_3 e^{-\left(\frac{T-t_0}{t3}\right)}$ ς_0 = 1.24527, ς_1 = 244.08345, ς_2 = 14.91657, ς_3 = 3.08744 t_0 = 154.2198, t_1 = 0.19883, t_2 = 1.24146, t_3 = 9.82364	0.99955
Thermal Conductivity (W/m-K)	154.78K ≤ T ≤ 204.58 K	$\kappa=\kappa_0+\varsigma_1 e^{-\left(\frac{T-t_0}{t_1}\right)}+\kappa_2 e^{-\left(\frac{T-t_0}{t_2}\right)}+\kappa_3 e^{-\left(\frac{T-t_0}{t3}\right)}$ κ_0 = 0.02241, κ_1 = 0.0121, κ_2 = 0.0103, κ_3 = 0.02471 t_0 = 154.44918, t_1 = 1.00673, t_2 = 6.14112, t_3 = 0.20075	0.99906
Viscosity (μPa-s)	154.78K ≤ T ≤ 182.08 K	$\mu=\mu_0+\mu_1 e^{-\left(\frac{T-t_0}{t_1}\right)}+\mu_2 e^{-\left(\frac{T-t_0}{t_2}\right)}+\mu_3 e^{-\left(\frac{T-t_0}{t3}\right)}$ μ_0 = 16.91312, μ_1 = 2.30219, μ_2 = 3.89607, μ_3 = 1.12772 t_0 = 154.75126, t_1 1.14041, t_2 = 6.06171, t_3 = 0.2442	0.99997
	182.18 K ≤ T ≤ 204.58K	$\mu=\mu_2+\frac{\mu_1-\mu_2}{1+e^{\left(\frac{T-t_0}{\mu_3}\right)}}$ μ_1 = 16.91214, μ_2 = 17.81706, μ_3 = 7.45775, t_0 = 201.77652	0.99984

IV. RESULTS AND DISCUSSIONS

To establish the accuracy of a fitted model, statistical parameters such as Arithmetic Average of the Absolute Values of the Relative Errors (AARE %) and Sum of Absolute Residuals (SAR) have been utilized. Small values of these parameters refer to reliable correlations. The Arithmetic Average of the Absolute Values of the Relative Errors (AARE %) [16-18] is determined by Eq. (3).

$$AARE\% = \frac{100}{N}\sum^{N}\left(\left|\frac{\chi^{exp}-\chi^{cal}}{\chi^{exp}}\right|\right) \quad (3)$$

Fig.6 shows the AARE% versus temperature for all the thermophysical properties of oxygen at critical pressure. Another such parameter is the Sum of Absolute Residuals (SAR) which is determined by Eq. (4) [16-18], which put forth the dependability of correlations for intense data sets.

$$SAR = \sum^{N} \left| \chi^{\exp} - \chi^{cal} \right| \tag{4}$$

The Average Percent Relative Error (ARE %) is determined by Eq. (5) [17-18], which gives an evaluation of the foregone conclusion of the correlations. A value of zero indicates a random of the measured values around the correlations.

$$ARE\% = \frac{100}{N} \sum_{i}^{N} \left(\frac{\chi^{\exp} - \chi^{cal}}{\chi^{\exp}} \right) \tag{5}$$

Fig.7, shows Percent Relative Error (RE %) as a function of temperature which is defined in Eq. (6) [16-18] for each thermophysical properties.

$$RE\% = 100 \times \left(\frac{\chi^{\exp} - \chi^{cal}}{\chi^{\exp}} \right) \tag{6}$$

It can be concluded from the Fig.7 that, with the increase in temperature, Relative Error is decreasing for the correlations developed. Moreover, the AARE%, ARE% and SAR values of the correlation developed for oxygen in comparison with the NIST values of every thermophysical properties is revealed in Table 2. It shows clearly the reliability of developed correlations for higher property values as a function of temperature. The correlations are valid for temperature ranges 154.78-204.58K at 50.43bars. Based on the above obtained results, the correlations developed along with correlation coefficients have good accuracy versus its simplicity.

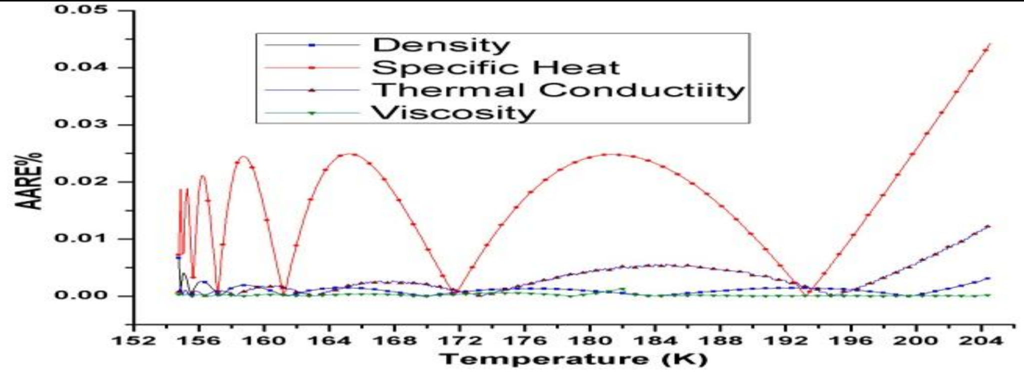

Fig 6: AARE% of correlations as function of temperature.

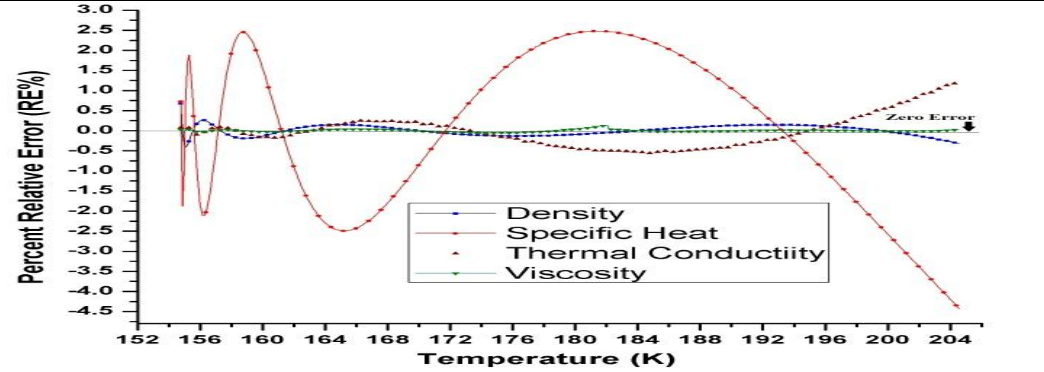

Fig 7: RE% of correlations as function of temperature

Table 2: Statistical value of each thermophysical properties at varying temperature

Properties	AARE%	ARE%	SAR
Density	**0.10477044**	**-0.000149326**	**84.432638**
Viscosity	**0.020773737**	**-2.42634E-05**	**1.813818518**
Specific Heat	**1.709004182**	**-0.032164604**	**16.94103535**
Thermal Conductivity	**0.310021664**	**-0.016527561**	**0.035447422**

V. CONCLUSION

The simple correlations have been proposed to accurately predict the density, specific heat, viscosity and thermal conductivity as a function of temperature in the present work. The advantages of using this correlation are that it does not need big computations and large number of variables, but shows splendid concord to that of NIST values. This novel correlation predicts the values of oxygen in temperatures ranging between 154.78K and 204.58K at critical pressure 50.43bar. The proposed correlation has resulted in lower AARE%, ARE% and SAR which identifies it as a dependable numerical approach for prior analysis of SMES power devices.

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