Development of Correlation for Thermophysical Properties of Supercritical Oxygen to Be Used in SMES

Aal Arif Sarkar, Abhinav Kumar, Preeti Rao Usurumarti, and Raja Sekhar Dondapati

Abstract-One of the most promising applications in High Temperature superconductor (HTS) is Superconducting Magnetic Energy Storage (SMES). At present, electrical storage systems reports 50-60% losses due to traditional use of conventional conductors. In order to overcome such challenges, HTS with efficient cooling must be employed in power applications. In the present work, a novel cooling concept with supercritical oxygen (SCO) has been proposed to maintain the superconducting state for wide range of applications. Moreover, the thermophysical properties such as viscosity, density, thermal conductivity and specific heat have been studied over a wide range of temperatures (154.58K-204.58K) and critical pressure 50.43bar. Further, the development of correlations for SCO above the critical temperature (T_c +50K), and at critical pressure (P_c+1bar) have been analyzed. The developed correlations can be used in predicting the performance of SMES power devices by prior modeling and simulations at various operating conditions.

Index Terms—Correlation, SMES, supercritical oxygen, and thermophysical properties.

I. INTRODUCTION

Nowadays, renewable energy sources (RESs) have recently become of particular interest, both in terms of intrinsically alternating resources and stability maintenance in electrical power systems [1]-[3]. Also, RESs power has been growing due to its immense availability and its truncated effect to the environment. However, these RESs power potential repeatedly changes and are barely predictable due to change in the environmental conditions. This can lead to undecorated complications due to severe fluctuations of tie-line power flow [4]. To overcome this problem, superconducting magnetic energy storage (SMES) can be utilized as an effective device with the ability to possess high storage efficiency, rapid response (within few milliseconds) and high cyclability, but only for short periods of time [5]. Essentially a SMES device comprises of three foundations: a magnet, a cryostat, and a connection system to the load [6]. The general components of the proposed SMES unit is shown in Fig. 1. In this study we focus mainly on the cryostat because of its emphasis on cooling the superconducting system. SMES are cryogenic devices, whose temperatures need to be kept sufficiently low to ensure non-dissipative operation of the

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high temperature superconducting (HTS) wires. The temperature is basically enacted by the cold source which is used and generally fixed before the SMES coil design. The isolation of coil cannot be done effortlessly from the outside because there are heat losses by radiation from the cryostat external surface, by conduction through the mechanical support of the coil, the cryostat and the current leads to connect it electrically. Moreover, current leads and networks between the superconducting wires are creating losses by Joule effect, while the coil winding itself generates heat during operation, when the conductor is close from its critical current. In consequence, a thermal system must be designed to ensure that the coil temperature is low enough to allow safe operation, with a reasonably homogenous and stable temperature. The cooling system has therefore to absorb this heat flux otherwise the temperature would slowly increase, which would progressively increase the heat dissipation and trigger a slow thermal runaway. Energy is therefore being dissipated in small volumes, also known as hot spots, where temperature rises rapidly. Thermal expansion in the hot spots might cause high mechanical stresses and possibly deformations to which high temperature superconducting (HTS) materials performances are highly vulnerable.



Fig. 1. General components of the proposed SMES unit.

Even if the conductor sustains the stress, when the temperature goes higher than the critical value the conductors linking might starts melting and the cryogens concentration in the superconducting material may get altered, which will ultimately cause the loss of superconducting properties. Therefore it is essential to have a good cryogenic fluid in the cryostat to bound the hotspots maximum temperature and the temperature gradients along the superconducting coil which requires an active protection [7]-[9]. Based on these facts, the aim of current work is to obtain novel cryogenic supercritical

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oxygen (SCO) fluid to be used in cryostat for cooling the high temperature superconducting (HTS) magnetic coil and bound the hotspots. Also we develop the explicit correlations for estimating the thermophysical properties of supercritical oxygen (SCO). The properties being a function of temperature and having wide range of applications is valid for temperature range from 155.78 to 204.58 K at pressure 50.53bar. The main aim is to verify the actual performance of the cooling system of the SMES using SCO, which will enable us to effectively increase the transient and dynamic stability of the power system.

II. THERMOPHYSICAL PROPERTIES OF SCO

The need to bind the thermal hotspots generated due to heating in the coil and to enhance the heat transfer process, the analysis for specific properties of SCO to be used in SMES has to be carried out. The emphasis of analysis is laid on the assumption of SCO having spherical molecules. Also considering the ability of SCO to conduct the heat generated in coil and 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 SCO enabled us to take advantage of a correct combination of the properties which is needed to be analyzed for the application of SCO in SMES. Therefore, for the novel SCO cryogen, 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. Fig. 3 illustrates the effect of temperature on viscosity at different pressures. It can be observed that with the increase in pressure, huge increase in the viscosity may be obtained in supercritical region. However, in the temperature range of 154.58K<T<181.48K, an initial decrease in viscosity is identified. In addition, a small increase in viscosity is observed at the end of the temperature range 181.48K < T < 204.58K due to the increase in density as can be seen from Fig. 3. Also, Fig. 2 shows the variation of density with temperature. In the pressure range of 50.43<*P*<51.33bar, exciting rise in density is observed. However, within the temperature of 154.58K<T<204.58K density is regularly decreasing. Fig. 4 shows the variation of specific heat with temperature. It can be observed that with increase in pressure from 50.43bar to 50.53bar drastic decrease in specific heat. In addition, a constant fall in specific heat with further increase in pressure from 50.63bar to 51.36bar. However, effect of temperature on specific heat results in development of pseudo-critical points in the temperature range of 154.58K<T<155.08K and pressure range of 50.53bar to 51.33bar. Furthermore, a linear drop in specific heat values is observed in the temperature range 155.08K<7<204.58K. Fig. 5 relates thermal conductivity as function of temperature at different pressures. The graph demonstrates significant decrease in thermal conductivity during 50.43<P<50.53bar. Subsequently gradual fall is observed with further increase in pressure. However, by raise in the temperature, curves reveals uniformly diminishing values of thermal conductivity in the temperature range of 154.58K<T<189.78K and linear increase in the values in the temperature range of 189.78K<T<204.58K.





From the above study of thermophysical properties, it is observed that supercritical fluid i.e., SCO exhibit desirable intermediate properties of both gas and liquid phases [10]-[15]. This may be due to the fact that when oxygen is heated until its specific critical temperature (154.58K) in a closed system, which means at constant pressure (50.43bar), a dynamic equilibrium is generated. This equilibrium includes the same number of molecules coming out of liquid phase to gas phase by gaining energy and going in to liquid phase from gas phase by losing energy thus affecting its molar volume. These co-existence of liquid and vapor at the same pressure with different molar volumes [16] leads to infinite isothermal compressibility at the critical point given by Eq. (1).

$$\left(\frac{\partial P}{\partial V}\right)_{T} = 0 \text{ and } \left(\frac{\partial^{2} P}{\partial^{2} V}\right)_{T} = 0 \tag{1}$$

This fluctuation in values results in the large inter-molecular distance, which is an indication of incipient instability near the critical points (154.58K and 154.68K) resulting in drastic drop in values of density, viscosity, specific heat and thermal conductivity of SCO.

However, due to this infinite compressibility factor, the increase in pressure at isotherms results in decreasing in intermolecular distance resulting in increase in the property values of density, viscosity, specific heat and thermal conductivity of SCO. This behavior depicts the property of SCO as a vapor. Moreover, at constant isochoric conditions when the temperature is increased, the specific gravity and isobaric heat capacity (degree of freedom) of SCO molecules also begins to increase in this region. As a result the diverging expansion coefficient of SCO molecules increases resulting in a smooth and gradual decrease in the property values. Thus, abruptly the viscosity, density, specific heat and thermal conductivity ascends from vapor-like to liquid-like values with variation in temperature.

III. DEVELOPMENT OF CORRELATION

Correlations have been developed in order to evaluate the variation of thermophysical properties with respect to temperature (T_C +50K) at critical pressure. These correlations were developed at critical pressure (50.43 bar) 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 in thermal modeling of SMES. Table I predicts that thermophysical properties of SCO at critical temperature and pressure. Table II shows various correlations with their correlation coefficient values. These new 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 =154.58K) and 154.68K of SCO was not considered for fitting at critical pressure (Pc=50.43bar). A Total of 500 data points for each property has been taken from NIST [17] and analyzed.

 TABLE I: THERMOPHYSICAL PROPERTIES AT CRITICAL TEMPERATURE

 (*Tc*=154.58K) AND PRESSURE (*Pc*=50.430 bar)

Critical	Thermophysical Properties			
(K)	Density (kg/m ³)	Viscosity (µPa-s)	Thermal conductivity (W/m-K)	Specific Heat (kJ/kg-K)
154.58	466.41	33.759	0.10442	719.48

IV. RESULTS AND DISCUSSIONS

To establish the accuracy of fitted model, statistical parameters such as Arithmetic Average of the Absolute Values of the Relative Errors (AARE%) and Sum of Absolute of Residual (SAR) have been utilized. Small values of these parameters refer to reliable correlation. The Arithmetic Average of the Absolute Values of the Relative Errors (AARE %) is defined in Eq. (2) [18]-[21].

$$AARE\% = \frac{100}{N} \sum^{N} \left(\left| \frac{\zeta^{\exp} - \zeta^{\operatorname{cal}}}{\zeta^{\exp}} \right| \right)$$
(2)

Fig. 6 shows the AARE% versus temperature for all the thermophysical properties of SCO at critical pressure. Another such parameter is the Sum of Absolute of Residual (SAR) which is defined in Eq. (3) [18]-[21], which put forth the reliability of correlation for more intense data points.

$$SAR = \sum^{N} \left| \zeta^{\exp} - \zeta^{\operatorname{cal}} \right| \tag{3}$$

The Average Percent Relative Error (ARE %) is defined in Eq. (4) [18], [19], [21], which gives a measure of the foregone conclusion of the correlation. A value of zero indicates a random of the measured values around the correlation.

$$ARE\% = \frac{100}{N} \sum^{N} \left(\frac{\zeta^{\exp} - \zeta^{cal}}{\zeta^{\exp}} \right)$$
(4)

Fig. 7, shows Percent Relative Error (RE %) as function of temperature which is defined in Eq. (5) [18]-[21] for each thermophysical properties.

$$RE\% = 100 \times \left(\frac{\zeta^{\exp} - \zeta^{cal}}{\zeta^{\exp}}\right)$$
(5)

It can be concluded from the Fig. 7 that, with increase in temperature relative error is decreasing for the correlation developed. It shows clearly the reliability of developed correlations for higher property values as a function of temperature. The AARE%, ARE% and SAR values of the correlation developed for SCO in comparison with the NIST values of every thermophysical properties is revealed in Table III. About the developed correlations, the AARE% at supercritical region is 0.120698633 for density, 0.223487687 for viscosity, 0.201117284 for specific heat and 0.193192467 for thermal conductivity in comparison with the NIST data.





Fig. 7. RE% of correlations as function of temperature.

TABLE II: DEVELOPED CORRELATIONS AND THEIR COEFFICIENTS FOR THERMOPHYSICAL PROPERTIES AT VARIOUS TEMPERATURE RANGE

Properties	Temperature Range	Correlation and Correlation Coefficients		
	154.78 K \leq T \leq 157.78 K	$\rho(T) = \frac{\rho_1 + \rho_2 * T}{\rho_0 + T}$	$ \rho_0 = -153.20, \rho_1 = -28833.47, \rho_2 = 189.54073 $	0.99846
Density	$157.88 \text{ K} \le T \le 169.98 \text{ K}$	$\rho(T) = \frac{\rho_1 + \rho_2 * T}{1 + \rho_0 * T}$	$ \rho_0 = -0.00687, \rho_1 = 87.06, \rho_2 = -0.67523 $	0.99988
	$170.08 \text{ K} \le T \le 204.58 \text{ K}$	$\rho(T) = \frac{\rho_1 + \rho_2 * T}{1 + \rho_0 * T}$	$\rho_0 = -0.00785, \rho_1 = 5.4524, \rho_2 = -0.35549$	0.99997
Viscosity	$154.78 \text{ K} \le T \le 157.78 \text{ K}$	$\mu(T) = \frac{\mu_1 + \mu_2 * T}{\mu_0 + T}$	$\mu_0 = -153.55, \mu_1 = -2710.190, \mu_2 = 17.69972$	0.99864
	157.88 K \leq T \leq 169.98 K	$\mu(T) = \frac{\mu_1 + \mu_2 * T}{1 + \mu_0 * T}$	$\mu_0 = -0.0066, \mu_1 = 15.92515, \mu_2 = -0.10606$	0.99996
	$170.08 \text{ K} \le T \le 185.28 \text{ K}$	$\mu(T) = \mu_0 + \mu_1 T + \mu_2 T^2 + \mu_3 T^3$	$\mu_0 = 209.80, \mu_1 = -2.92, \mu_2 = 0.0146, \mu_3 = -2.42E-5$	0.99903
	$185.38K \le T \le 204.58 K$	$\mu(T) = \mu_0 + \mu_1 T + \mu_2 T^2 + \mu_3 T^3$	$\mu_0 = 116.3, \mu_1 = -1.46, \mu_2 = 0.00706, \mu_3 = -1.11E-05$	0.99999
Specific heat	154.78 K \leq T \leq 157.78 K	$c_p(T) = \frac{c_{p1} + c_{p2} * T}{c_{p0} + T}$	$c_{p0} = -154.48, c_{p1} = -324.77, c_{p2} = 2.15127$	0.99958
	$157.88 \text{ K} \le T \le 169.98 \text{ K}$	$c_p(T) = \frac{c_{p1} + c_{p2} * T}{c_{p0} + T}$	$c_{p0} = -153.63, c_{p1} = -144.49, c_{p2} = 1.0286$	0.99996
	$170.08 \text{ K} \le T \le 204.58 \text{ K}$	$c_p(T) = \frac{c_{p1} + c_{p2} * T}{1 + c_{p0} * T}$	$c_{p0} = -0.00661, c_{p1} = 0.7434, c_{p2} = -0.00572$	1
Thermal Conductivity	154.78 K \leq T \leq 157.78 K	$\kappa(T) = \frac{\kappa_1 + \kappa_2 * T}{\kappa_0 + T}$	$\kappa_0 = -154.00116, \kappa_1 = -3.82176, \kappa_2 = 0.02492$	0.99824
	157.88 K \leq T \leq 169.98 K	$\kappa(T) = \frac{\kappa_1 + \kappa_2 * T}{\kappa_0 + T}$	$\kappa_0 = -151.82955, \kappa_1 = -3.07204, \kappa_2 = 0.02056$	0.99999
	$170.08 \text{ K} \le T \le 185.28 \text{ K}$	$\kappa(T) = \kappa_0 + \kappa_1 T + \kappa_2 T^2 + \kappa_3 T^3$	$\kappa_0 = 0.90, \kappa_1 = -0.014, \kappa_2 = 7.4\text{E}-05, \kappa_3 = -1.33\text{E}-07$	0.99998
	$185.38 \text{ K} \le T \le 204.58 \text{ K}$	$\kappa(T) = \kappa_0 + \kappa_1 T + \kappa_2 T^2 + \kappa_3 T^3$	$\kappa_0 = 0.219, \ \overline{\kappa_1} = -0.002, \ \kappa_2 = 1.3E-05, \ \kappa_3 = -2.14E-08$	0.99999

TABLE III: STATISTICAL VALUE FOR EACH THERMOPHYSICAL PROPERTIES AT VARYING TEMPERATURE AND PRESSURE

Properties	AARE%	ARE%	SAR
Density	0.120698633	0.099056855	104.569232
Viscosity	0.223487687	-0.213166932	19.70022503
Specific heat	0.201117284	-0.105039577	3.879817087
Thermal Conductivity	0.19319 2467	-0.235407374	0.029946928

Also the values of ARE% for each thermophysical properties i.e., density, viscosity, specific heat and thermal conductivity are 0.099056855, 0.2131669323, 0.105039577 and 0.23540734 respectively. It means that the correlations should be preferred over the NIST correlations. For this purpose 500 data points for each density, viscosity, specific

heat and thermal conductivity have been selected. The temperature ranges of the data are 154.78-204.58K at 50.43bar. Based on the obtained results in Fig. 6, Fig. 7 and Table III, the correlations developed along with correlation coefficients have good accuracy versus its simplicity.

V. CONCLUSION

An easy-to-use correlation has been proposed to accurately predict the density, specific heat, viscosity and thermal conductivity as a function of temperature in the present work. The main advantage of using this correlation is that it does not need big computations and large number of parameters but shows splendid concord to that of NIST values. The predictions showed admirable contract with those reported in the NIST. This novel correlation predicts the values of SCO in temperatures ranging between 154.78K and 204.58K for critical pressure 50.43bar. The proposed correlation has resulted in lower AARE%, ARE% and SAR which identifies it as a dependable approach for prior analysis of SMES power devices.

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