Development of correlation for Thermophysical properties of supercritical Argon to be used in futuristic HTS cables

Mohit Kalsia [1], Abhinav Kumar[1], Preeti Rao Usurumarti[2], Raja Sekhar Dondapati[1]

1 School of Mechanical Engineering, Lovely Professional University, Phagwara, Punjab 144 401, India

2 Department of Mechanical Engineering, P.V.K.Inst of Technology, Anantapur, Andhra Pradesh, India

ABSTRACT

Most of the power transmission systems are to be replaced by high temperature superconducting (HTS) cables for efficient operation. These HTS cables need to be cooled below the critical temperature of superconductors used in constructing the cable. With the advent of new superconductors whose critical temperatures having reached up to 134K (Hg based), need arises to find a suitable coolant which can accommodate the heating load on the superconductors. In order to accomplish such challenge an attempt has been made in the present work to identify suitable Thermophysical properties of supercritical argon (SCAR). The Thermophysical properties such as density, viscosity, specific heat and thermal conductivity of SCAR found to be drastically varying with respect to temperature at a particular pressure. Moreover, it is observed that with an increase in pressure density and viscosity are increasing. In addition, as the temperature increases a shift in Thermophysical properties is observed. Few correlations are developed which are applicable over a wide range of temperatures. These correlations may be useful in thermohydraulic modeling of HTS cables using numerical or computational techniques. In recent times, with the sophistication of computer technology, solving of various transport equations with temperature dependent thermophysical properties became popular and hence the developed correlations would benefit the technological community.

INTRODUCTION

High Temperature Superconducting (HTS) Cables are used in large scale power transmission systems. However, these cables require attention with regard to design, manufacturing [1-4], laying and safe operation. In order to safely operate [5-9] these HTS cables, efficient cooling methodologies must be employed with judicious selection of coolant [10]. Supercritical fluids, due to their peculiar properties, may be employed in cooling HTS cables.

Thermophysical properties, such as density, viscosity, thermal conductivity, specific heat and other properties vary significantly as the pressure and temperature of fluid exceeds above the critical values. HTS cable with single layer of HTS tapes is shown in Figure 1. In this context, it is important to consider the properties of superconducting materials, sheath materials, former material, dielectric materials, electrical shielding, thermal insulators and properties of coolants at cryogenic temperatures while designing of the HTS cables. The properties of each material stated above at cryogenic temperatures vary considerably and depend on the operating temperature (T_0). These issues necessitate the study of thermophysical properties applicable to the design of HTS cables.

STUDY OF THERMOPHYSICAL PROPERTIES

In order to understand the flow and heat transfer behaviour of Supercritical Argon (SCAR), few thermophysical properties such as Density, Thermal conductivity, Viscosity, Specific heat are plotted with respect to the temperature above supercritical region. Further, correlations were developed for thermophysical properties of SCAR and compared with the standard data available from NIST [13]. It is found that the deviation from the standard values is minimum as discussed in the later section.

Figure 2 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 150.79K<T<165K, an initial decrease in viscosity is identified. In addition, a small increase in viscosity is observed at the end of the temperature range 165K<T<200.69K due to the increase in density as can be seen from Figure 3. Also, Figure 3 shows the variation of density with temperature. In the pressure range of 4.863<P<5.863bar, extreme rise in density is observed due to the higher compression resulting in lesser intermolecular distance of the fluid. However, with in the temperature of 150.69K<T<200.69K density is regularly decreasing.

Figure 4 shows the variation of specific heat with temperature. It can be observed that with increase in pressure from 4.863bar to 4.963bar drastic decrease in specific heat. In addition, a constant fall in specific heat with further increase in pressure from 5.063bar to 5.86bar. However, effect of temperature on specific heat results drastic decrease in the temperature range of 150.69K<T<154.89K. Furthermore, a sudden increase in the range of 154.89K<T<156.59K and then a linear fall in the range 156.59K<T<200.69K is observed.

Figure 5 relates thermal conductivity as function of temperature at different pressures. The graph demonstrates significant decrease in thermal conductivity during 4.863<P<4.963bar, 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 150.69K<T<200.69K.

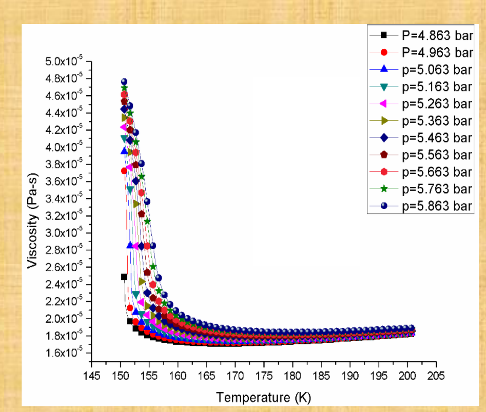

Figure 2 Viscosity as function of temperature at different pressures

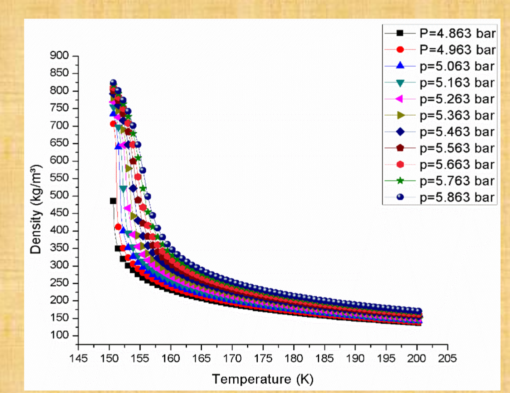

Figure 3 Density as function of temperature at different pressures

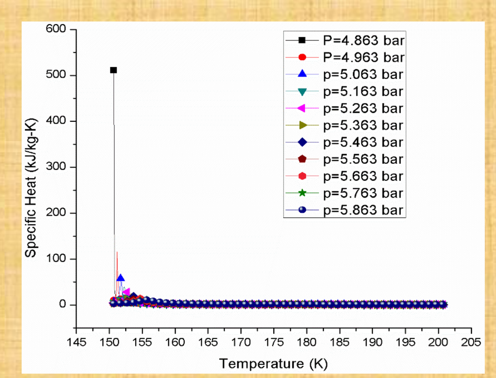

Figure 4 Specific Heat as function of Temperature at different pressures

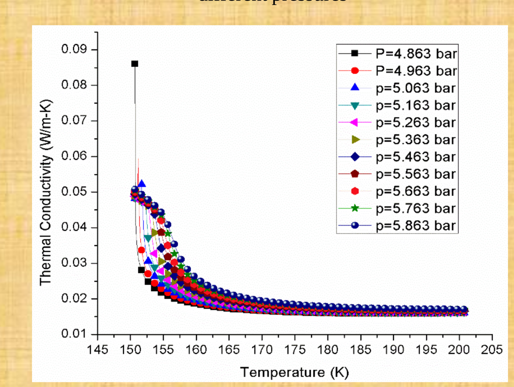

Figure 5 Thermal conductivity as function of Temperature at different pressures

CORRELATION AND TABLES

The correlations and the correlation coefficients obtained from fitting are compiled in Table 1. The novelty of the correlations developed [11-12] is that minimum number of correlation coefficients are sufficient to express the correlation unlike the polynomial correlation. It is found that the developed correlations as accurate as 98% to 99% as can be seen from the Table 1.

Properties	Temperature Range	Correlations	Correlation Coefficient		R²-Value
Density (ρ) (kg/m³)	150.79K ≤ T ≤ 152.59K	$\rho=(\rho_2+T)/(\rho_1+\rho_3*T)$	ρ_1	-0.56814	0.99783
			ρ_2	-149.38433	
			ρ_3	0.00379	
	152.69 K ≤ T ≤ 200.69K	$\rho=(\rho_2+T)/(\rho_1+\rho_3*T)$	ρ_1	-1.63179	0.99832
			ρ_2	-94.16334	
			ρ_3	0.01196	
Specific heat (C_p) (kJ/kg-K)	150.79 K ≤ T ≤ 152.79K	$C_p=(C_{p2}+T)/(C_{p1}+C_{p3}*T)$	c_{p1}	-72.2299	0.99952
			c_{p2}	-148.33689	
			c_{p3}	0.47948	
	152.89 K ≤ T ≤ 200.69 K	$C_p=(C_{p2}+T)/(C_{p1}+C_{p3}*T)$	c_{p1}	-276.3881	0.99961
			c_{p2}	-128.44319	
			c_{p3}	1.84851	
Viscosity (μ) (Pa-s)	150.79 K ≤ T ≤ 155.79 K	$\mu=(\mu_2+T)/(\mu_1+\mu_3*T)$	μ_1	-8.81516E6	0.99633
			μ_2	-149.3863	
			μ_3	58884.83131	
	150.89 K ≤ T ≤ 170.89 K	$\mu=(\mu_2+T)/(\mu_1+\mu_3*T)$	μ_1	-9.05276E6	0.98785
			μ_2	-152.46242	
			μ_3	59305.42314	
	170.99 K ≤ T ≤ 200.69 K	$\mu=(\mu_2+\mu_3*T)/(1+\mu_1*T)$	μ_1	-0.00386	0.99905
			μ_2	1.55599E-5	
			μ_3	-5.71495E-8	
Thermal Conductivity (κ) (W/m-K)	150.79 K ≤ T ≤ 152.79K	$\kappa=(\kappa_2+T)/(\kappa_1+\kappa_3*T)$	κ_1	-7051.18647	0.99639
			κ_2	-149.94681	
			κ_3	46.89732	
	152.89 K ≤ T ≤ 200.69 K	$\kappa=(\kappa_2+T)/(\kappa_1+\kappa_3*T)$	κ_1	-10040.23758	0.99202
			κ_2	-146.17691	
			κ_3	67.44997	

RESULTS AND DISCUSSION

Statistical parameters have been used to find the accuracy of the fitted model and correlations. Small values of parameters refer to consistent correlation. Here, the Eq. (1) defines the Arithmetic Average of the Absolute Values of the Relative Errors (AARE %).

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

The steadiness of correlation for concentrated data points can be stated by another parameter called Sum of Absolute of Residual (SAR) which is defined in Eq. (2).

$$SAR = \sum^{500}\left|X^{act}-X^{cal}\right| \qquad (2)$$

Here, an extent of the predictable conclusion of the correlation given by the Average Percent Relative Error (ARE %) is defined in Eq. (3). A value of zero indicates a random of the measured values around the correlation.

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

For each thermophysical properties correlation as function of temperature, Percent Relative Error (RE %) is defined in Eq. (4)

$$RE\% = 100\times\left(\frac{X^{act}-X^{cal}}{X^{act}}\right) \qquad (4)$$

Eq. (5), expresses the standard error relation of developed correlations for higher property values as a function of temperature.

$$Xerror = \left(X^{\exp}-X^{cal}\right) \qquad (5)$$

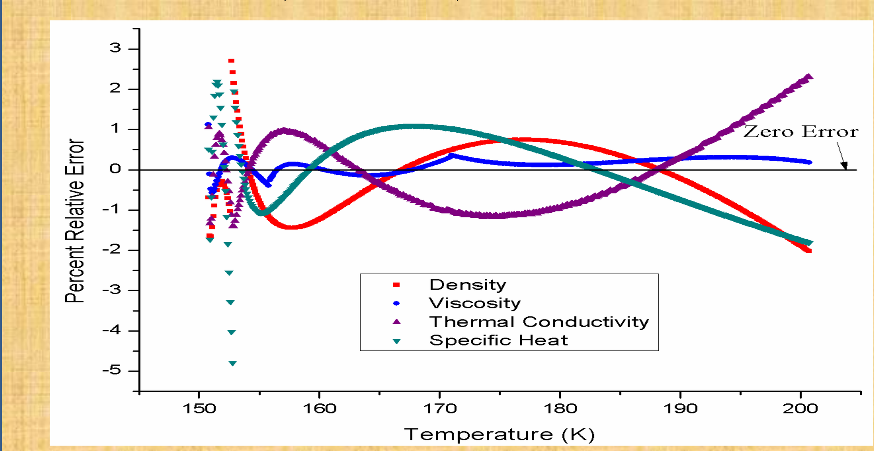

Figure 6 RE% of correlations as function of temperature

Properties	AARE%	ARE%	SAR
Density	0.729007468	-0.2335741	712.9714
Viscosity	0.187613051	1.32E-01	1.6627E-05
Specific heat	0.825611	-0.06596	7.046078
Thermal Conductivity	0.811473684	-0.0061487	0.069885

With regard to Figure 6 percent relative error of correlations as function of temperature can be seen. At initial an increase in the temperature from 150.69K to 154K, maximum error is obtained. However, further increase in the temperature shows a very less variation in relative error.

CONCLUSION

- In order to calculate accurately various thermophysical properties, the correlations are being proposed in this work and the developed correlation were compared with standard data from NIST [13]. Moreover, the thermophysical properties of supercritical Argon portrays interesting facts on pressure and temperature distribution in HTS cable.
- This work also explains the phenomenon of flow occurrence with less pumping power and maximum heat transfer through coolant in HTS cables. It can be concluded that in the temperature range of 195K<T<200.69K at P=4.963bar, the density of SCAR would be minimum. However, the viscosity of SCAR is expected less value in the temperature range of 157.5K<T<172.5K at P=4.963 bar above the supercritical region. Moreover, this study would help in continuous flow of coolant with minimum pumping power.
- In order to increase the heat transfer, higher value of specific heat of SCAR is needed at P=5.063bar in the temperature range of 151K<T<152.5K. However, the thermal conductivity of SCAR is expected higher value at P=5.063 bar in the temperature range of 150.79K<T<155K.

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