Development of Correlations for Thermophysical Properties of Supercritical Hydrogen in High Temperature Superconducting (HTS) Generators

Mugilan.S [a], Idris.S.M[a], Abhinav Kumar[a], Gaurav Vyas[a], Preeti Rao Usurumarti[b], Raja Sekhar Dondapati [a]

[a]*School of Mechanical Engineering, Lovely Professional University, Phagwara, Punjab 144 401, India*

[b]*Department of Mechanical Engineering, P.V.K.Inst of Technology, Anantapur, Andhra Pradesh, India*

Abstract

The storage and generation of power has been a main objective over the past decade. To accomplish such an objective, superconductors are introduced in 1978, which observed a sublime growth in power generation systems. However, electrical losses such as AC losses and thermal losses due to conduction, convection and radiation in those superconductors are inevitable. In order to overcome and reduce these losses, use of cryogenic fluids above their critical temperature is necessary. One such fluid being studied in this work is supercritical hydrogen (SCH). Various thermophysical properties such as density, viscosity, thermal conductivity and specific heat of SCH were studied. The results reveal that with the rise in temperature there is a radical change in thermophysical properties of SCH. Besides, few correlations have been developed for the same at various pressures and temperatures. The developed correlations are elaborated such that, the use of supercritical hydrogen (SCH) may be explored in the HTS generator for improving its performance. Due to the dynamic nature of HTS generators, unlike HTS cables, the cooling requires careful attention and precise monitoring.

Introduction

- ❖The work reported here uncovers the thermophysical properties of supercritical hydrogen (SCH) to be utilized in HTS generators.
- ❖Due to the reduced size, weight and higher power system stability HTS generators were preferred over conventional generators.
- ❖For developing long life of HTS generators, SCH with desirable properties are being considered and subjected to further scrutiny for replacing conventional coolants.
- ❖Though there have been significant research work carried out in the field of supercritical fluids, the concentration on SCH is minimal.

Conclusion

- ❖The correlations which are simple to exploit are being proposed in this work, to accurately predict the various thermophysical properties as a function of temperature and pressure.
- ❖ This model was obtained from 500 experimental measurements and is valid in temperature range from 33.191K - 83.191K, and pressures range between 1.315MPa and 2.215MPa.
- ❖The major boon of using this correlation is that it does not need large number of parameters.
- ❖The projected correlation has generally resulted in minimum values of RE% in comparison with the NIST [14] web book data.

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Thermophysical properties of SCH

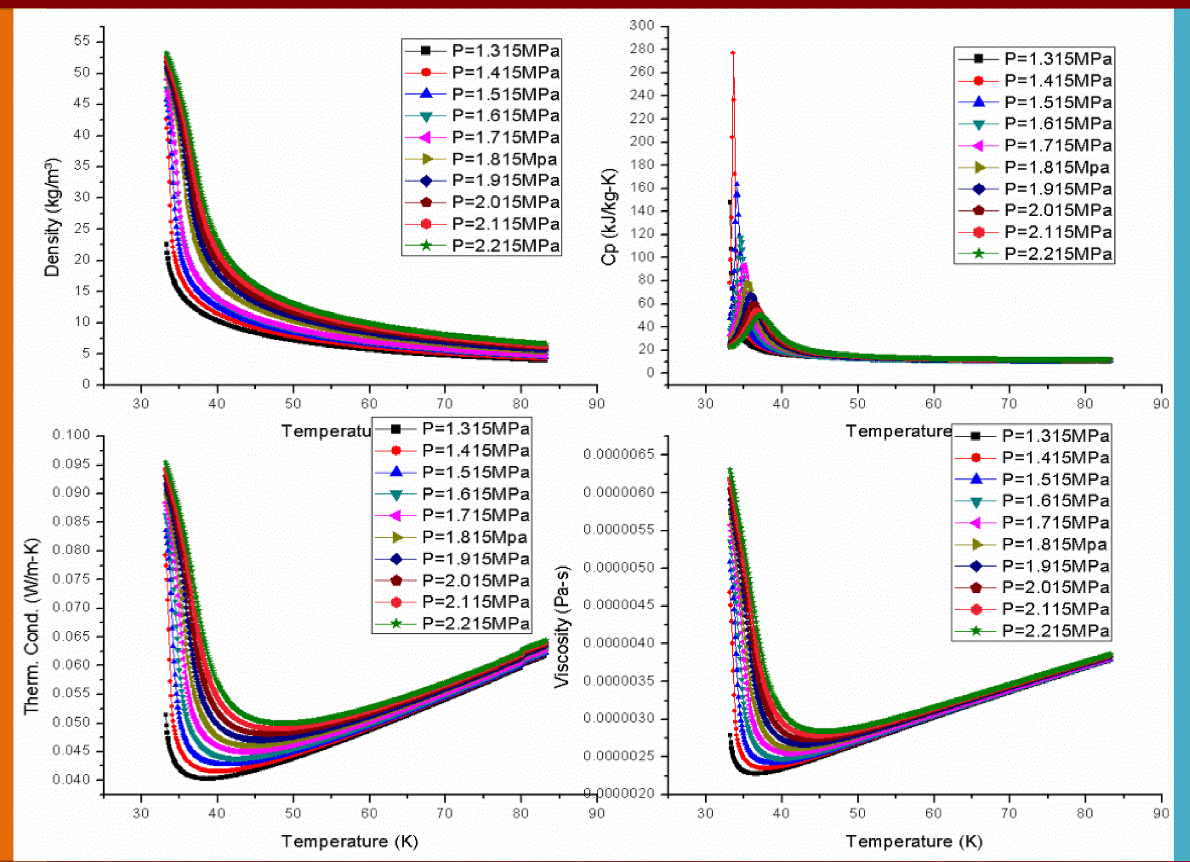

Figure. 1. Density, Thermal conductivity, Specific heat and Viscosity at varying temperature and pressure .

- ❖The simple single phase correlations such as Dittus-Boelter-Nusselt correlation and Gnielinski correlation cannot accurately capture the heat transfer behaviours in the near critical temperature region because it is sensitive to the variations of the thermophysical properties.
- ❖The four properties which are taken into consideration in this work are: Density, Thermal conductivity, Viscosity, Specific heat.
- ❖Figure 1 shows the thermophysical properties of SCH as a function of temperature at varying pressure. At constant pressure, Cp value decreases as temperature increases.
- ❖However, as the pressure increases corresponding values of specific heat increases. The Cp lines at different pressures shown in Figure 1 are identical with respect to temperature.
- ❖On the contrary, there is a sudden fall in thermal conductivity followed by gradual increase in temperature. Figure 1 draws down the conclusion of inferior flow with compact heat absorption with respect to thermal conductivity. An overview of the density graph shows a decrease in the value of density with the increase in temperature. A sudden change in the density value is observed above the critical temperature T_c. In the case of viscosity, the value of viscosity tends to fall at initial, however gradually increases with increase in temperature. The paths carried out by viscosity at various pressures are identical with slender variation. That slight variation in the value is fitted and errors are calculated. The plunge in viscosity proves improved flow rate of SCH. Furthermore, the temperature range taken into consideration while plotting the graph is from 33.191K - 83.191K.

Results and Discussion

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. (1).

$$AARE\% = \frac{100}{N}\sum_{i=1}^{499}\left(\left|\frac{X^{exp} - X^{cal}}{X^{exp}}\right|\right) \quad (1)$$

Another such parameter is the Sum of Absolute of Residual (SAR) which is defined in Eq. (2), which put forth the reliability of correlation for more intense data points.

$$SAR = \sum^{499}\left|X^{exp} - X^{cal}\right| \quad (2)$$

The Average Percent Relative Error (ARE %) is defined in Eq. (3), 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.

$$ARE\% = \frac{100}{N}\sum_{i=1}^{499}\left(\frac{X^{exp} - X^{cal}}{X^{exp}}\right) \quad (3)$$

Figure 5 shows Percent Relative Error (RE %) which is defined in Eq. (4) for each thermophysical properties as a function of temperature and pressure.

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

Correlations Table

Properties	Temperature Range	Correlation and Correlation Coefficients			Adj. R- Value
Density (ρ) (kg/m³)	33.191K ≤ T ≤ 58.091K	$\rho = (\rho_2 + \rho_3 * T)/(1 + \rho_1 * T)$	ρ_0	-0.0343	0.99395
			ρ_1	1.52593	
			ρ_2	-0.13217	
	58.191 K ≤ T ≤ 83.191K	$\rho = 1.0/(\rho_0 + \rho_0 * T + \rho_2 * T)$	ρ_0	-0.05832	0.99628
			ρ_1	0.00427	
			ρ_2	-5.74E-06	
Specific heat ( ) (kJ/kg-K)	33.191 K ≤ T ≤ 34.191 K	$C_p = (C_{p1} + T)/(C_{p0} + C_{p2} * T)$	Cp_0	0.05121	0.99896
			Cp_1	0.06239	
			Cp_2	0.06239	
	34.291 K ≤ T ≤ 40.091 K	$C_p = (C_{p1} + T)/(C_{p0} + C_{p2} * T)$	Cp_0	0.00211	0.99956
			Cp_1	0.02122	
			Cp_2	7.48475E-5	
Viscosity (μ) (μPa-s)	33.191 K ≤ T ≤ 36.091 K	$\mu = (\mu_1 + \mu_2 * T)/(1 + \mu_0 * T)$	μ_0	-0.03049	0.99394
			μ_1	0.00218	
			μ_2	-6.66E-05	
	36.191 K ≤ T ≤ 83.191K	$\mu = 1.0/(\mu_0 + \mu_0 * T + \mu_2 * T)$	μ_0	720.1547	0.99893
			μ_1	-9.06962	
			μ_2	0.04334	
Thermal Conductivity (κ) (W/m-K)	33.191 K ≤ T ≤ 38.091K	$\kappa = (1 + \kappa_2 T)/(\kappa_0 + \kappa_1 * T)$	κ_0	25.46085	0.99189
			κ_1	-0.75723	
			κ_2	-0.02983	
	38.191 K ≤ T ≤ 38.991 K	$\kappa = 1.0/(\kappa_0 + \kappa_1 * T + \kappa_2 * T^2)$	κ_0	35.66388	0.99803
			κ_1	-0.296	
			κ_2	7.37E-04	

Table 1. Correlations for thermophysical properties of SCH for various temperature range at Pc=1.315MPa.

Table 1 shows the developed correlations, correlation coefficient at anecdotal temperature ranges for various thermophysical properties. These correlations were developed with an accuracy of 99% with minimum variables for more efficient calculations and results. Rational type is preferred over other coefficients due to minimal coefficients.

Error analysis

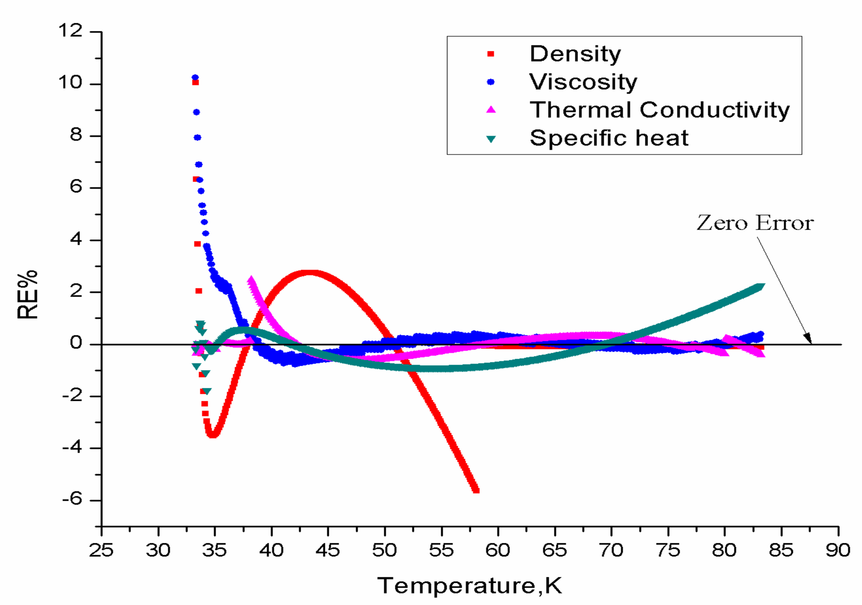

Figure 2 RE% of correlations as function of temperature

- ❖The RE% sinks down with gradual increase in temperature, which is shown in above Figure 2.
- ❖It is evident that with the decline in value RE%, higher accuracy and precise flow of SCH can be attained in HTS generators

Properties	AARE%	ARE%	SAR
Density	1.127258224	-0.095453231	51.53836
Viscosity	0.459410202	0.233573648	0.005964
Specific heat	0.690231059	0.00121674	47.71263023
Thermal Conductivity	0.307556957	-0.002299476	0.070829131

Table 2 Statistical value for each thermophysical properties at P_c=1.315Mpa

The AARE%, ARE% and SAR values of the correlation developed for SCH in comparison with the NIST values of every thermophysical properties is revealed in **Table 2.**

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