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Theoretical Development of Thermodynamic Properties of an Environmental Friendly Refrigerant RE170 by Using Martin Hou Equation of State

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ABSTRACT

This paper deals with the theoretical development of thermodynamic properties of an environmental friendly refrigerant dimethylether (RE170). Since hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs) are going to be phase out and phase down as per Montreal and Kyoto protocol respectively. Refrigerant RE170 has zero ozone depletion potential (ODP) and very low global warming potential (GWP) which is less than two. Hence RE170 is considered as a viable option to replace for the refrigerants with GWP like HFCs. RE170 can be used as blend component with other ecofriendly refrigerant. The main objective of the present study is to compute the thermodynamic properties of RE170 by using Martin Hou equation of state (MH EOS). These properties are useful to do the thermodynamic analysis of a vapour compression refrigeration cycle. The properties computed are saturation vapour pressure, liquid density, vapour specific volume, enthalpy and entropy (both in the saturated liquid and vapour state). In the present study a MATLAB code is developed to compute the above considered thermodynamic properties from the temperature about 131.6K-398.15K and pressure up to 51.3bar. The computed properties of dimethylether is compared with NIST REFPROP database. Since thermodynamic properties of RE170 are not available in ASHRAE hand book and also in the literature. Therefore NIST REFRPROP can be considered as a reliable source as that of ASHRAE. The results shows that the absolute average deviation (AAD) of liquid and vapour phase enthalpy from that of NIST REFPROP is 1.01% and 0.319% respectively. Similarly AAD of liquid and vapour phase entropy is 1.05% and 0.25% respectively. Deviation of vapour specific volume and liquid density is 1.49% and 0.25% respectively. AAD of saturation pressure is 0.071%. Overall the computed thermodynamic properties of RE170 by using MHEOS shows good agreement with NIST REFPROP database for wide the temperature range about 131.6K-398.15K and pressure up to 51.3bar.

1. INTRODUCTION

Montreal protocol has been taken the decision to ban the refrigerant R22 completely by the year 2030 (UNEP, 1987, Powell, 2002). Because R22 has adverse ecological impacts like high ozone depletion potential (ODP) and high global warming potential (GWP). Therefore it is necessary to develop the refrigerants which possess zero ODP and low GWP. Thermodynamic properties were required to conduct the performance investigation of any given refrigerants. Hence the present study focuses on development of thermodynamic properties of an ecofriendly refrigerants. Earlier several studies has been carried out to establish the properties of the refrigerants. Barret and Candau were computed the thermodynamic properties of refrigerants like R125 and R143a using MHEOS (Barret and Candau, 1992). Results showed that data obtained from the equation of state for R143a matches well with experimental data of refrigerant R143a. Theoretical thermodynamic properties modeling of two R22 alternatives like R410A and R407C were done by using MHEOS (De Monte, 2002a). Effect of temperature on thermodynamic property of two R22 alternatives like R410A and R407C was established along with the predominant effect of pressure in describing these properties (De Monte, 2002b). Investigation on predicting the liquid density and vapour

pressure of the dimethylether was done based on artificial neural networks with back-propagation algorithm (Moghadassi et al., 2010). Prediction of above properties exhibited good agreement with the experimental data. The thermodynamic property modeling for the RE170 was developed by using the experimental thermodynamic property data (Jiangtao Wu et al., 2011). Investigation of thermodynamic properties of refrigerant R1234yf was estimated by using various cubic equation of state models (Anant Agrawal et al., 2012). The properties obtained from these models were validated against most reliable NIST-REFPROP data base (Lemmon et al., 2013). The present work focuses on the theoretical thermodynamic property modeling and development of properties for the refrigerant RE170 by using Martin-Hou equation of state. The various properties of RE170 are validated with most reliable NIST-REFPROP data base. Because thermodynamic properties of RE170 are not available in ASHRAE hand book and also in the literature. Hence NIST REFRPROP can be considered as reliable source as that of ASHRAE.

2. Properties of Dimethylether (RE170)

The basic physical properties and enviriomental properties of refrigerant dimethylether (RE170) are shown in table1.

Table 1: Properties of refrigerant RE170

Properties	**RE170**
Molecular weight (kg/kmol)	46.068
Normal boiling point at 1.01325 bar (ºC)	-24.78
Critical temperature (K)	400.38
Critical pressure (MPa)	5.336
ODP	0
GWP (100 years)	1

From the table 1 it is noticed that RE170 has zeo ODP and negilgible GWP. Therefore RE170 can be considered as an ecofriendly refrigerant. RE170 can be used as blend component with other ozone friendly HFC refrigerants in order to reduce the GWP of blend and also to improve the performance of the blend. An improvement in COP of the blend depends on the, how much composition of RE170 is going to be mix. For this thermodynamic analysis of various refrigerant blends consists of RE170 as one of the component blends is to be done. In this regard the present authors were computed the theoretical thermodynamic performance of various blends consists of RE170 at air conditioning conditions like T_e=280K and T_k=328K (Sharmas Vali Shaik and T.P. Ashok Babu, 2017). Authors were neglected various losses occurred in the cycle while doing the performance study of various blends. The performance results of various blends are given in the table 2.

Table 2: Thermodynamic performance results of R22 alternatives (Sharmas Vali Shaik and T.P. Ashok Babu, 2017)

Refrigerant	Composition (mass %)	COP	Change in COP (%)	T_d (ºC)	VRC (kJ/m^3)
R22	Pure refrigerant	4.003	0	78.09	3646
NRM10 (R32/R134a/R290)	17.5/80/2.5	3.437	-14.13	76.64	2788
NRM20 (R32/R134a/R290)	25/67.5/7.5	3.389	-15.33	79.46	3050
NRM30 (R134a/R1270/RE170)	55/37.5/7.5	4.217	5.34	66.18	3267
NRM40 (R134a/R290/RE170)	55/37.5/7.5	4.075	1.79	65.01	2786
R407C (R32/R125/R134a)	23/25/52	3.231	-19.28	78.07	3172

From the table 2 it is observed that the ternary refrigerant blend consists of R134a, R1270 and RE170 i.e. NRM30 (R134a/R1270/RE170 55/37.5/7.5 by mass %) has 5.34% higher COP compared to base line refrigerant R22. Apart from NRM30 and NRM40 also has considerable increase in COP compared to R22. From these results it is evident

that blending the RE170 as one of the component in small composition enhances the performance of the system. This is the main driving force or basic motivation to study and develop the thermodynamic properties of RE170.

3. METHODOLOGY AND CORRELATIONS

The various correlations used to establish the thermodynamic properties are given in this section. P-h chart used while developing the properties is shown in figure1. The methodolgy and step by step procedure followed to develop the properties of given refrigerant (RE170) is explained in below (Arora, 2009).

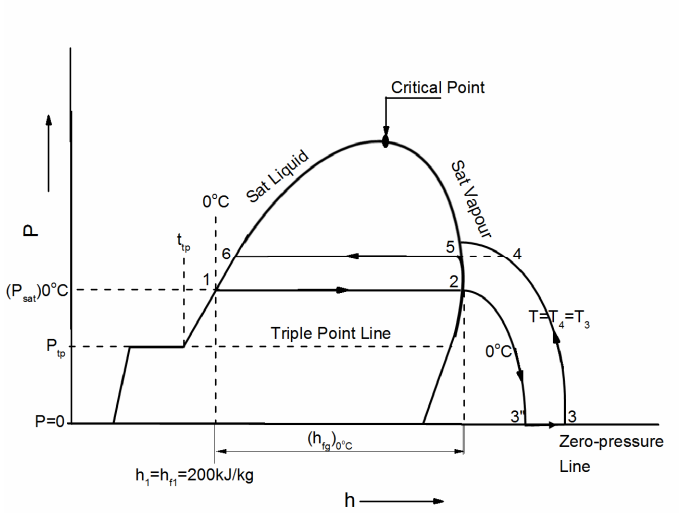


Figure 1 : P-h diagram used for calculating the properties of refrigerant

3.1 Saturation Pressure

Wagner vapour pressure correlation is used to compute the saturation pressure of the given refrigerant RE170.

$$\ln\left(\frac{P_{sat}}{P_c}\right)=\left(\frac{1}{1-x}\right)\left[Ax+Bx^{1.5}+Cx^{2.5}+Dx^{5}\right] \tag{1}$$

Where $x=1-\frac{T}{T_c}$; A, B, C and D are constants for a partcular rerigrigerants. These constants for RE170 are avialable in the literature and they are shown in table 3 (Luis A Forero and Jorge A Velásquez, 2011).

Table 3: Constants for Equation (1)

A	B	C	D
-6.9798	1.523	-1.6409	-2.7943

3.2 Liquid density

Ried et.al correlation is used to find the liquid density of the given refrigerant RE170 (Reid et al., 1977, Khashayar Nasrifar and Mahmood Moshfeghian, 1999).

$$\rho_r=\frac{\rho}{\rho_c}=1+0.85\left(1-T_r\right)+\left(1.6916+0.984\omega\right)\left(1-T_r\right)^{1/3} \tag{2}$$

Where ω is accentric factor and $T_r = \frac{T}{T_c}$; ω, ρ_c T_c are constants and they are taken from the literature and given in table 4 (Bruce E Poling et al., 2001).

Table 4: Constants for Equation (2)

ω	ρ_c (kg/m3)	T_c (K)
0.19	273.65	400.38

3.3 Specific Volume of Vapour

Specific volume of vapour for the refrigerant RE170 is computed by using Martin-Hou equation of state (Martin Joseph J and Yu-Chun Hou., 1955).

$$P = \frac{RT}{v-b} + \frac{A_2 + B_2T + C_2e^{-5.475T/T_c}}{(v-b)^2} + \frac{A_3 + B_3T + C_3e^{-5.475T/T_c}}{(v-b)^3} + \frac{A_4}{(v-b)^4} + \frac{B_5T}{(v-b)^5} \quad (3)$$

The dimensionless coefficients for the refrigerant RE170 obtained from the above Martin-Hou equation of state are shown in table 5.

Table 5: Dimensionless coefficients of RE170 for Equation (3)

A2= -498.4594	B2= 0.3933	C2= -1.2235X10^4
A3= 2.0780	B3= -0.0029	C3= 35.4344
A4= -0.0015	B5= 2.0087X10^{-9}	b= 9.2042X10^{-4}

3.4 Enthalpy of Vapourization

Clausis-Clapreyon equation is used to compute the enthalpy of vapourization of the refrigerant RE170.

$$\frac{dP_{sat}}{dT} = \frac{h_{fg}}{TV_{fg}} = \frac{h_{fg}}{T(v_g - v_f)} \quad (4)$$

Before computing the properties, the reference state for enthalpy and entropy is to be fixed. İn this study the reference state for the enthalpy and entropy is Href=200 kJ/kg, Sref=1kJ/kgK for the saturated liquid at 0^{o}C is taken.

3.5 Departure Method

The siginficance of departure function is, to compute the enthlapy amd entropy at various points as shown in the P-h diagram (Arora, 2009). To compute the enthalpy at point 3, the enthalpy departure mrthod is used.

The enthalpy departure term h_3-h_2 is given by

$$h_3 - h_2 = (U_3 - U_2) + (P_3V_3 - P_2V_2) \quad (5)$$

$$U_3 - U_2 = \int_2^3 \left[T\left(\frac{\partial P}{\partial T}\right)_V - P \right] dV \quad (6)$$

By solving the equations (5) and (6) the value of h_3 can be found.

İnorder to find the enthalpy h_4 at point 4, ideal heat capacity correlation and ethalpy difference (h_4-h_3) can be used.

$$h_4 - h_3 = \int_3^4 C_{P0}\,dT \quad (7)$$

İn the present work ideal heat capacity C_{P0} correlation is taken from the literature (Bruce E Poling et al., 2001).

$$C_{P0} = A_0 + A_1T + A_2T^2 + A_3T^3 + A_4T^4 \quad (8)$$

Where A_0, A_1, A_2, A_3, and A_4 are constants for a particular refrigerant. These constants for RE170 are taken from the literature and they are given in table 6 (Bruce E Poling et al., 2001).

Table 6: Constants for Equation (8)

A_0	A_1	A_2	A_3	A_4
4.361	$6.070X10^{-3}$	$2.899X10^{-5}$	$-3.581X10^{-8}$	$1.282X10^{-11}$

Again enthalpy departure term is used in between the state points 4 and 5 in order to find enthlapy h_5.

$$h_5 - h_4 = (U_5 - U_4) + P_5V_5 + P_4V_4 \tag{9}$$

$$U_5 - U_4 = \int_4^5 \left[T\left(\frac{\partial P}{\partial T}\right)_V - P \right] dV \tag{10}$$

By solving the equations (9) and (10) the value of h_5 can be found.

The saturated liquid enthalpy at state point 6 can be found by using the following relation.

$$h_5 - h_6 = h_{fg} \tag{11}$$

Where h_{fg} is found by using Clasius-Clayperon equation at a given temperature. Therefore

$$h_6 = h_5 - h_{fg} \tag{12}$$

3.6 Liquid Entropy

To compute the thermodynamic properties (enthalpy and entropy) of refrigerant at any given pressure and temperature, the departure method is used and the corresponding saturated liquid enthalpy and saturated liquid entropy is calculated using the Clausius-Clapeyron equations.

Entropy of liquid for the given refrigerant can be calculated as

$$S_{fg} = S_g - S_f$$
$$S_f = S_g - S_{fg} \tag{13}$$

3.7 Vapour Entropy

Entropy of vapour for the given refrigerant can be computed by

$$S_{fg} = \frac{h_{fg}}{T_{sat}} \quad S_g = \frac{h_g}{T_{sat}} \tag{14}$$

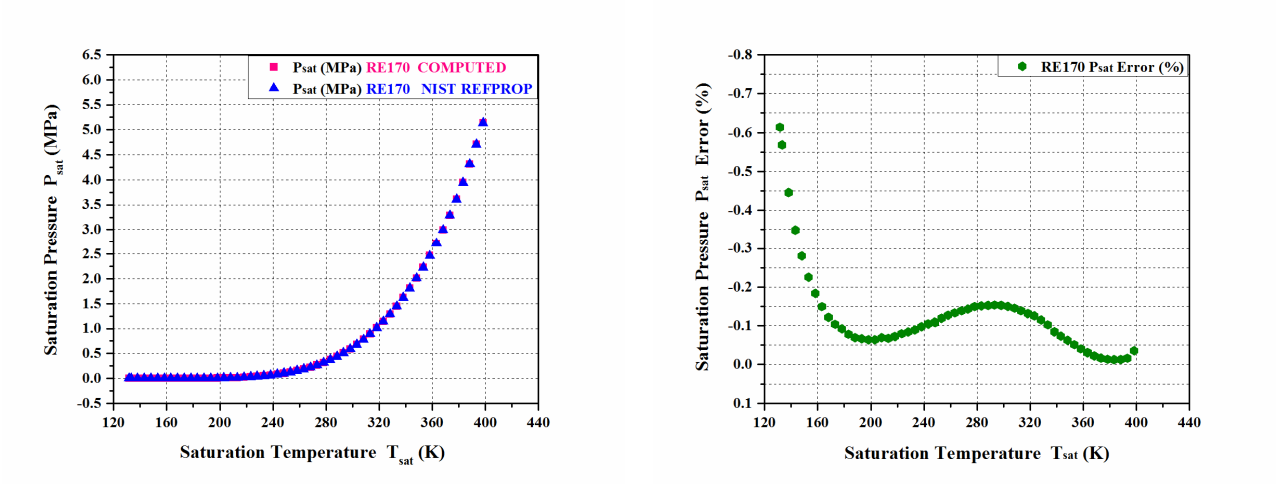
By following the above methodology the thermodynamic properties are computed for the refrigerant RE170 of wide temperature range from about 131.6K-398.15K and pressure up to 51.3 bar. The computed thermodynamic properties are shown in table 7. The results and discussions on the development of properties of refrigerant RE170 are given below.

4. RESULTS AND DISCUSSIONS

4.1 Comparison of Computed P_{sat} with NIST REFPROP P_{sat} for RE170

Wagner vapour pressure correlation is used to compute the saturation pressure of the refrigerant RE170. From the figure 2(a) and 2(b) it is noticed that the computed saturation pressure values shows good agreement with NIST REFPROP and percentage error obtained for the computed saturation pressure for RE170 is ranging from -0.150% to -0.114% for the given air conditioner operating temperature range between 280 to328 K. It may also be noted that deviation of saturation pressure varies from -0.61% to -0.03% for the temperature range 131K-363K. Whereas

absolute average deviation (AAD) of saturation pressure is 0.071% for the wide temperature range about 131.6K-398.15K and wide pressure range about $2.21x10^{-5}$-51.3 bar.

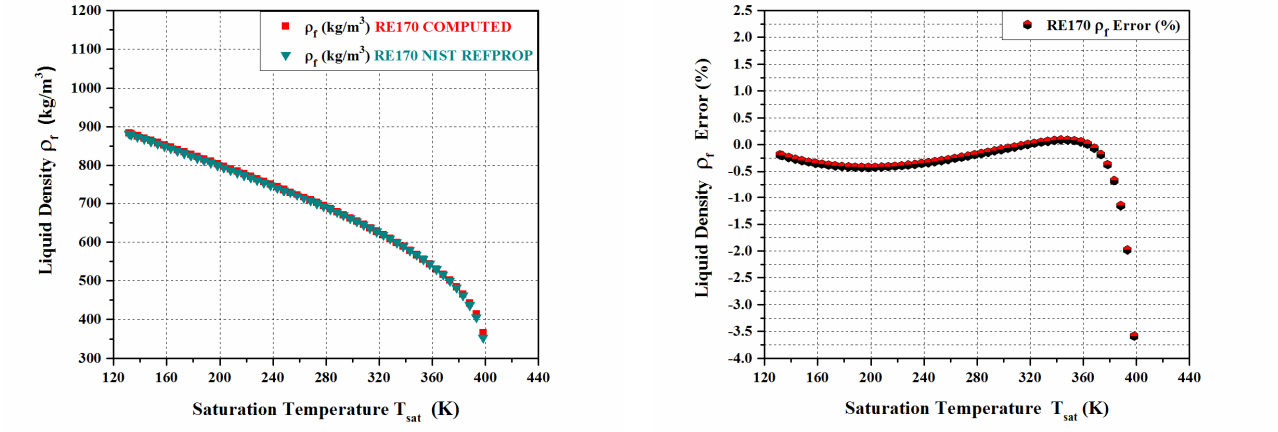


(a) (b)

Figure 2: (a) Comparison of computed P_{sat} with NIST as a function of temperature (b) Deviation of P_{sat} with NIST

4.2 Comparison of Computed ρ_f with NIST REFPROP ρ_f for RE170

Reid method is used to compute the saturated liquid density of the refrigerant RE170. From the figure 3(a) and 3(b) it is noticed that the computed density values shows good agreement with NIST REFPROP data base and percentage error obtained for the computed density for RE170 is ranging from -0.179% to -0.045% for the given air conditioner operating temperature range between 280 to328 K. It may also be noted that deviation of saturation pressure varies from -0.19% to 0.0088% for the temperature range 131K-363K. Whereas absolute average deviation (AAD) of liquid density is 0.253% for the wide temperature range about 131.6K-398.15K and wide pressure range about $2.21x10^{-5}$-51.3bar.



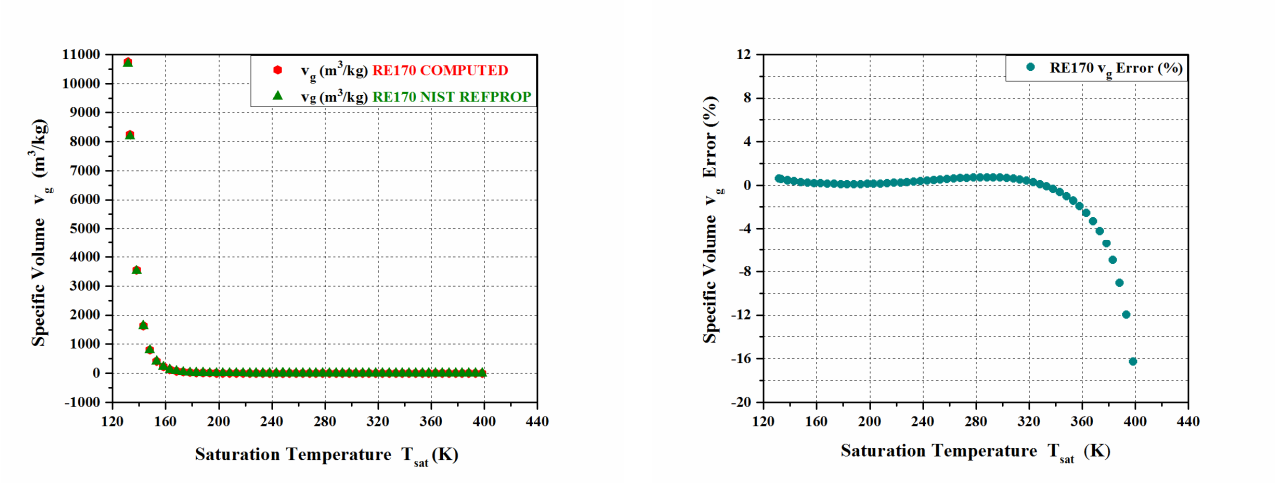
(a) (b)

Figure 3: (a) Comparison of computed ρ_f with NIST as a function of temperature (b) Deviation of ρ_f with NIST

4.3 Comparison of Computed V_g with NIST REFPROP V_g for RE170

Martin-Hou equation of state is used to compute the specific volume of vapour refrigerant RE170. From the figure 4(a) and 4(b) it is noticed that the computed vapour specific volume values shows good agreement with NIST REFPROP data base and percentage error obtained for the computed vapour specific volume for RE170 is ranging from 0.708% to 0.108% for the given air conditioner operating temperature range between 280 to328 K. It may also

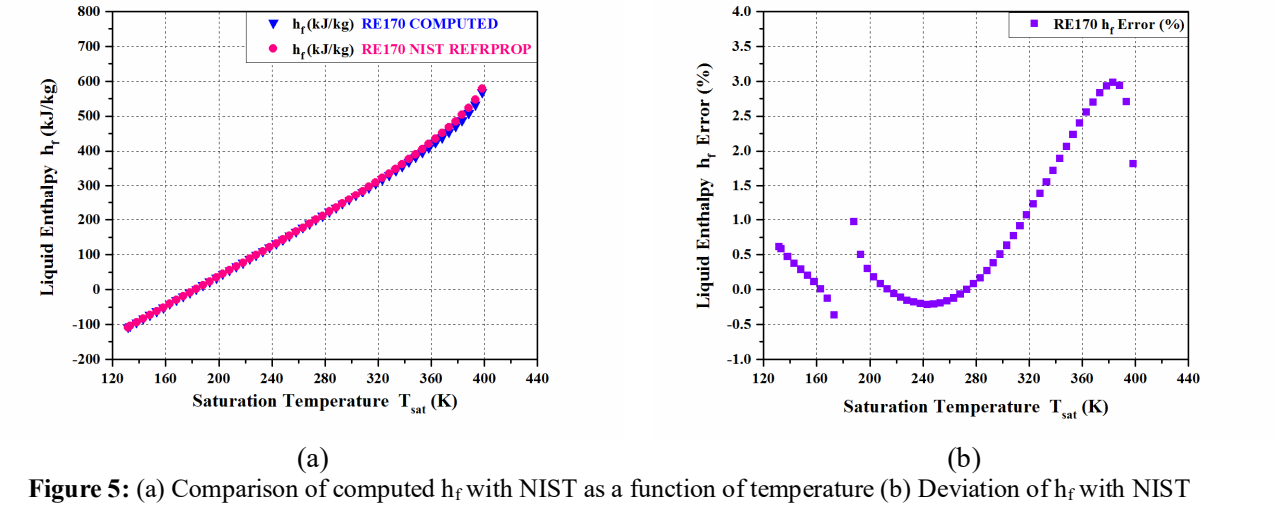
be noted that deviation of saturation pressure varies from 0.61% to -2.54% for the temperature range 131K-363K. Whereas absolute average deviation (AAD) of vapour specific volume is 1.49% for the wide temperature range about 131.6K-398.15K and wide pressure range about 2.21x10^{-5}-51.3bar.



(a) (b)

Figure 4: (a) Comparison of computed V_g with NIST as a function of temperature (b) Deviation of V_g with NIST

4.4 Comparison of Computed h_f with NIST REFPROP h_f for RE170



(a) (b)

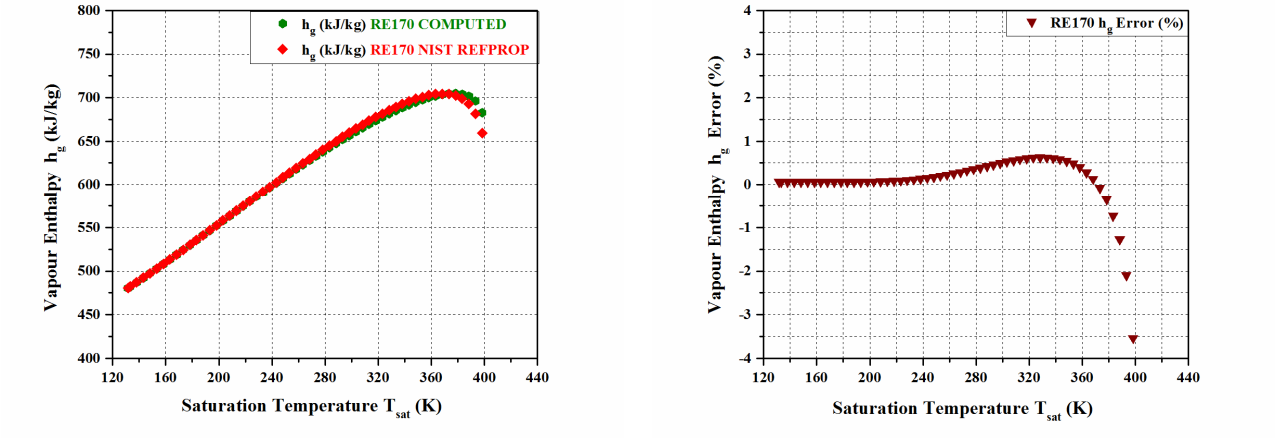
Figure 5: (a) Comparison of computed h_f with NIST as a function of temperature (b) Deviation of h_f with NIST

Enthalpy departure method and latent heat of vapourization is used to compute the liquid enthalpy of the given refrigerant RE170. From the figure 5(a) and 5(b) it is noticed that the computed liquid enthalpy values shows good agreement with NIST REFPROP data base and percentage error obtained for the computed liquid enthalpy for RE170 is ranging from 0.114% to 1.387% for the given air conditioner operating temperature range between 280 to 328 K. It may also be noted that deviation of liquid enthalpy varies from 0.61% to 2.55% for the temperature range 131K-363K. Whereas absolute average deviation (AAD) of liquid enthalpy is 1.01% for the wide temperature range about 131.6K-398.15K and wide pressure range about 2.21x10^{-5}-51.3bar.

4.5 Comparison of Computed h_g with NIST REFPROP h_g for RE170

Enthalpy departure method and latent heat of vapourization is used to compute the vapour enthalpy of the given refrigerant RE170. From the figure 6(a) and 6(b) it is noticed that the computed vapour enthalpy values shows good agreement with NIST REFPROP data base and percentage error obtained for the computed vapour enthalpy for

RE170 is varies from 0.372% to 0.627% for the given air conditioner operating temperature range between 280 to328 K. It may also be noted that deviation of liquid enthalpy varies from 0.067% to 0.283% for the temperature range 131K-363K. Whereas absolute average deviation (AAD) of vapour enthalpy is 0.319% for the wide temperature range about 131.6K-398.15K and wide pressure range about 2.21x10^{-5}-51.3bar.

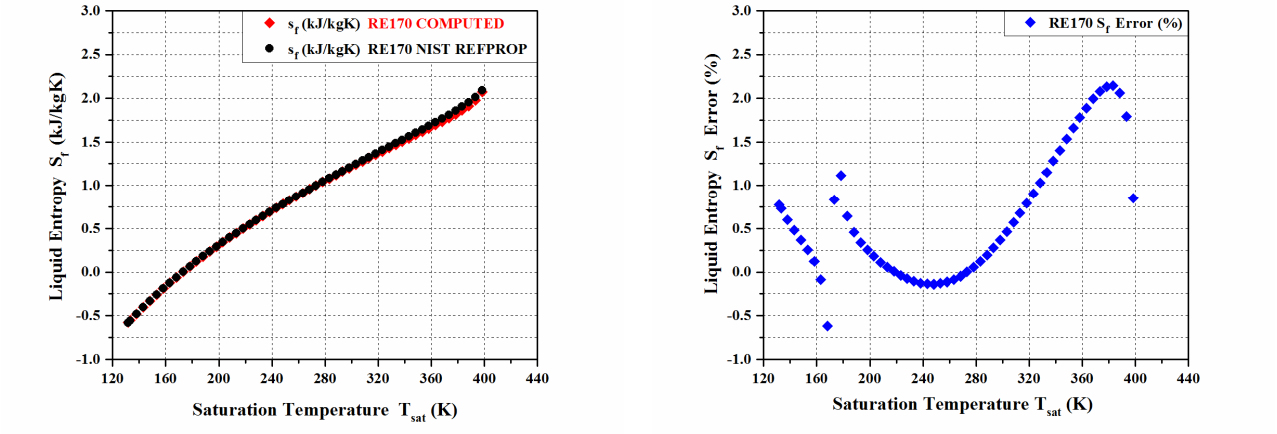


(a) (b)

Figure 6: (a) Comparison of computed h_g with NIST as a function of temperature (b) Deviation of h_g with NIST

4.6 Comparison of Computed S_f with NIST REFPROP S_f for RE170

The departure method and Clasius-Clayperon is used to compute the liquid entropy of the given refrigerant RE170. From the figure 7(a) and 7(b) it is noticed that the computed liquid entropy values shows good agreement with NIST REFPROP data base and percentage error obtained for the liquid entropy for RE170 is varies from 0.082% to 1.032% for the given air conditioner operating temperature range between 280 to328 K. It may also be noted that deviation of liquid entropy varies from 0.775% to 1.889% for the temperature range 131K-363K. Whereas absolute average deviation (AAD) of liquid entropy is 1.055% for the wide temperature range about 131.6K-398.15K and wide pressure range about 2.21x10^{-5}-51.3bar.

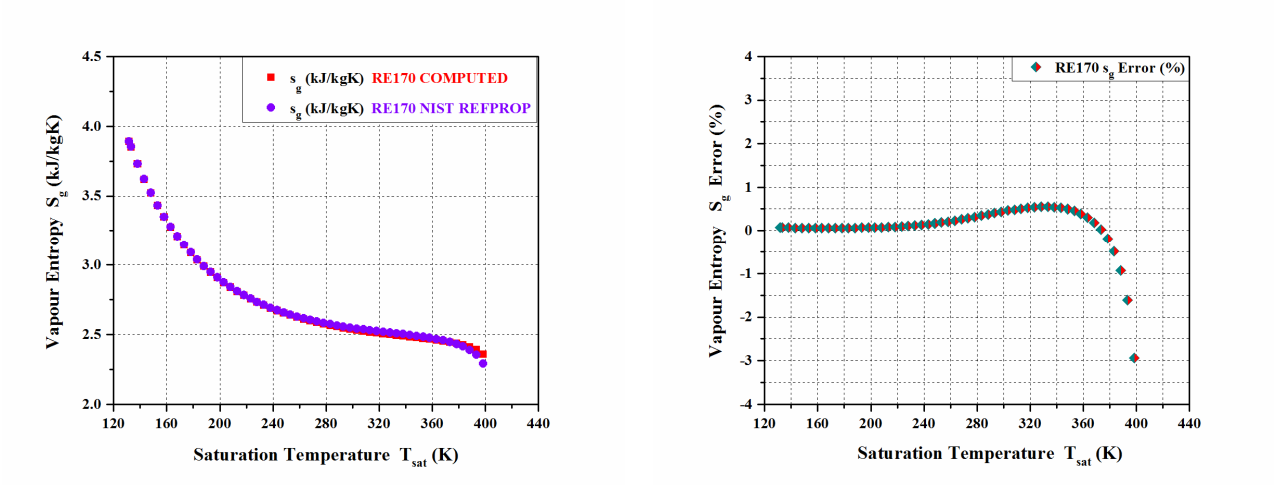


(a) (b)

Figure 7: (a) Comparison of computed S_f with NIST as a function of temperature (b) Deviation of S_f with NIST

4.7 Comparison of Computed S_g with NIST REFPROP S_g for RE170

The departure method and Clasius-Clayperon is used to compute the vapour entropy of the given refrigerant RE170. From the figure 8(a) and 8(b) it is noticed that the computed vapour entropy values shows good agreement with NIST REFPROP data base and percentage error obtained for vapour entropy for RE170 is varies from 0.329% to 0.550% for the given air conditioner operating temperature range between 280 to328 K. It may also be noted that deviation of vapour entropy varies from 0.078% to 0.305% for the temperature range 131K-363K. Whereas absolute average deviation (AAD) of vapour entropy is 0.262% for the wide temperature range about 131.6K-398.15K and wide pressure range about $2.21x10^{-5}$-51.3bar.



(a) (b)

Figure 8: (a) Comparison of computed S_g with NIST as a function of temperature (b) Deviation of S_g with NIST

6. CONCLUSIONS

In this work an attempt was made to compute and develop the thermodynamic properties of an ecofriendly refrigerant dimethylether (RE170) for the wide temperature range about 131.6-398.15K and pressure up to 51.3 bar. MH EOS was used for this purpose. In this study thermodynamic properties generated were validated against NIST REFPROP database. Martin-Hou equation of state was found to be an appropriate equation of state in the operating temperature region (280-328K) of residential air conditioner. Since the deviation of all the computed and developed properties (P_{sat}, ρ_f, V_g, h_f, h_g, S_f and S_g) were within 1% compared with NIST REFPROP database. It was noticed that for the temperature range (131-363K), the deviation of thermodymic properties were within 2.5%. This study exhibited there was considerable increase in deviation of properties as the computation approaches to critical point or critical region. Also in this study absolute average deviation (AAD) of above properties were also found. AAD of saturated pressure and liquid density was 0.071% and 0.25% respectively for the entire temperature range 131.6-398.15K and pressure up to 51.3 bar. AAD of saturated vapour phase of both enthalpy and entropy was 0.31% and 0.26% whereas for saturated liquid phase of enthalpy and entropy was 1.01 and 1.05% respectively for the entire temperature and pressure range. AAD of vapour specific volume of RE170 was 1.49% for the wide temperature range 131.6-398.15K and pressure up to 51.3bar. However average absolute deviation (AAD) of all the properties were within 1.05% as the temperature was approaches near to critical region. Hence the developed thermodynamic properties of refrigerant RE170 by using MH EOS were reliable and these properties would be useful and applicable for analyzing and computing the thermodynamic performance characteristics of vapour compression refrigeration system.

Table 7: Refrigerant RE170 (Dimethylether) Properties of Saturated Liquid and Saturated Vapor

T (K)	Pressure (Mpa)	Liquid Density (kg/m3)	Vapour Volume (m3/kg)	Enthalpy (kJ/kg)		Entropy (kJ/kgK)	
				Liquid	Vapour	Liquid	Vapour
131.66	2.2242E-06	883.86	10682.29356	-107.89	480.34	-0.5790	3.8888
133.15	2.9331E-06	882.160	8192.18123	-104.74	481.84	-0.5552	3.8502
138.15	7.0676E-06	876.410	3527.48119	-94.17	486.92	-0.4773	3.7290
143.15	1.5893E-05	870.623	1625.39118	-83.58	492.07	-0.4020	3.6193
148.15	3.3599E-05	864.799	795.67201	-72.97	497.29	-0.3291	3.5200
153.15	6.7202E-05	858.936	411.20933	-62.35	502.56	-0.2586	3.4299
158.15	0.00012787	853.033	223.13248	-51.72	507.89	-0.1903	3.3481
163.15	0.00023261	847.088	126.51628	-41.10	513.28	-0.1242	3.2737
168.15	0.00040626	841.100	74.64093	-30.46	518.71	-0.0600	3.2060
173.15	0.00068378	835.067	45.64904	-19.83	524.20	0.00228	3.1442
178.15	0.00111282	828.989	28.84503	-9.183	529.72	0.06290	3.0879
183.15	0.00175637	822.862	18.77648	1.47	535.28	0.12191	3.0364
188.15	0.00269547	816.686	12.55792	12.15	540.86	0.17943	2.9894
193.15	0.00403188	810.457	8.60910	22.85	546.47	0.2355	2.9464
198.15	0.00589054	804.175	6.03692	33.59	552.09	0.2904	2.9071
203.15	0.00842179	797.837	4.32179	44.35	557.71	0.3440	2.8710
208.15	0.01180316	791.440	3.15324	55.16	563.33	0.3965	2.8379
213.15	0.01624089	784.982	2.34111	66.00	568.94	0.4480	2.8076
218.15	0.02197088	778.460	1.76624	76.89	574.53	0.4985	2.7797
223.15	0.02925920	771.872	1.35233	87.83	580.10	0.5480	2.7540
228.15	0.03840225	765.213	1.04960	98.82	585.63	0.5966	2.7304
233.15	0.04972633	758.481	0.82492	109.85	591.12	0.6444	2.7086
238.15	0.06358700	751.672	0.65589	120.94	596.57	0.6914	2.6886
243.15	0.08036796	744.782	0.52710	132.08	601.96	0.7376	2.6701
248.15	0.10047978	737.806	0.42782	143.27	607.29	0.7830	2.6530
248.3	0.10113909	737.596	0.42522	143.60	607.45	0.7844	2.6525
253.15	0.12435837	730.741	0.35044	154.51	612.56	0.8278	2.6372
258.15	0.15246334	723.580	0.28950	165.80	617.77	0.8718	2.6226
263.15	0.18527626	716.318	0.24105	177.14	622.90	0.9151	2.6091
268.15	0.22329901	708.949	0.20218	188.54	627.97	0.9578	2.5966
273.15	0.26705208	701.465	0.17072	199.99	632.95	0.9999	2.5850
278.15	0.31707309	693.860	0.14506	211.51	637.85	1.0415	2.5743
283.15	0.37391542	686.126	0.12398	223.08	642.67	1.0824	2.5643
288.15	0.43814710	678.251	0.10653	234.72	647.40	1.1228	2.5550
293.15	0.51034996	670.227	0.09200	246.42	652.04	1.1628	2.5464
298.15	0.59111913	662.041	0.07981	258.21	656.59	1.2022	2.5384
303.15	0.68106284	653.680	0.06953	270.07	661.03	1.2413	2.5309
308.15	0.78080273	645.128	0.06081	282.02	665.36	1.2799	2.5239
313.15	0.89097455	636.369	0.05337	294.07	669.58	1.3181	2.5173
318.15	1.01222948	627.381	0.04699	306.23	673.68	1.3561	2.5111
323.15	1.14523597	618.141	0.04149	318.50	677.64	1.3938	2.5051
328.15	1.29068245	608.621	0.03673	330.92	681.45	1.4312	2.4994
333.15	1.44928073	598.788	0.03259	343.49	685.10	1.4685	2.4939
338.15	1.62177059	588.603	0.02897	356.24	688.56	1.5057	2.4885
343.15	1.80892558	578.016	0.02579	369.19	691.82	1.5428	2.4831
348.15	2.01156046	566.967	0.02299	382.37	694.84	1.5801	2.4776
353.15	2.23054083	555.379	0.02050	395.84	697.58	1.6175	2.4720
358.15	2.46679561	543.155	0.01829	409.661	700.01	1.6554	2.4661

363.15	2.72133375	530.162	0.01631	423.89	702.05	1.6937	2.4597
368.15	2.99526684	516.220	0.01452	438.65	703.62	1.7330	2.4527
373.15	3.28984138	501.066	0.01290	454.11	704.60	1.7736	2.4449
378.15	3.60648690	484.301	0.01142	470.51	704.80	1.8161	2.4357
383.15	3.94689377	465.262	0.01004	488.29	703.95	1.8619	2.4247
388.15	4.31315377	442.696	0.00873	508.27	701.48	1.9131	2.4108
393.15	4.70806695	413.656	0.00743	532.42	696.12	1.9752	2.3916
398.15	5.13612895	366.312	0.00591	568.66	682.66	2.0714	2.3578

NOMENCLATURE

h	Enthalpy	(kJ/kg)
h_f	Liquid enthalpy	(kJ/kg)
h_{fg}	Enthalpy of vapourization	(kJ/kg)
h_g	Vapour enthalpy	(kJ/kg)
P	Pressure	(MPa)
P_c	Critical pressure	(MPa)
P_{sat}	Saturation pressure	(MPa)
R	Universal gas constant	(J/mol K)
S_f	Liquid entropy	(kJ/kgK)
S_g	Vapour entropy	(kJ/kgK)
T	Temperature	(K)
T_c	Critical temperature	(K)
T_d	Compressor discharge temperature	(°C)
T_{sat}	Saturation temperature	(K)
U	Internal energy	(kJ/kg)
V_g	Vapour specific volume	(m^3/kg)
ρ_c	Critical density	(kg/m^3)
ρ_f	Liquid density	(kg/m^3)

Greek Letters

ρ	Density	(kg/m^3)
ω	Acentric factor	Dimensionless

Subscript

c	Critical
f	Liquid phase
g	Vapour phase

REFERENCES

Anant Agrawal., Avi Anthony Cornelio., & Dirk Limperich. (2012). Investigation of Cubic EOS Models for HFO-1234yf Refrigerant Used In Automotive application. *Proceedings of the 14th International Refrigeration and Air Conditioning Conference, Purdue* (2253 P1- 2253 P10). USA.

Arora, C.P. (2009). *Refrigeration and air Conditioning*. New Delhi India: Tata McGraw Hill.

Barret, M. & Candau, Y. (1992). Thermodynamic Properties Computation of Two Possible Substitute Refrigerants: R143a (1, 1, 1-trifluoroethane) and R125 (Pentafluoroethane). *Proceedings of the International Refrigeration and Air Conditioning Conference, Purdue* (Paper 182), 433-442. USA.

Bruce E Poling., John M Prausnitz., & John P. O'Connell. (2001). *The Properties of Gases and Liquids*. New York: McGraw-Hill.

De Monte, F. (2002a). Calculation of thermodynamic properties of R407C and R410A by the Martin–Hou equation of state - part I: theoretical development. *Int. J. Refrig.*, *25*(3), 306-313.

De Monte, F. (2002b). Calculation of thermodynamic properties of R407C and R410A by the Martin–Hou equation of state - part II: technical interpretation. *Int. J. Refrig.*, *25*(3), 314-329.

Jiangtao Wu., Yong Zhou., & Eric W. Lemmon. (2011). An Equation of State for the Thermodynamic Properties of Dimethyl Ether. *J. Phys. Chem. Ref. Data., 40*(2), 1-16.

Khashayar Nasrifar & Mahmood Moshfeghian. (1999). Evaluation of saturated liquid density prediction methods for pure refrigerants. *Fluid Ph. Equilibria., 158*, 437–445.

Lemmon, E.W., Huber M.L., & McLinden, M.O. (2013), NIST Reference Fluid Thermodynamic and Transport Properties-REFPROP, NIST Standard Reference Database 23-Version 9.1

Luis A Forero G., & Jorge A Velásquez J. (2011). Wagner liquid–vapour pressure equation constants from a simple methodology. *J. Chem. Thermodyn., 43*(8), 1235-1251.

Martin Joseph J. & Yu-Chun Hou. (1955). Development of an Equation of State for Gases. *AIChE Journal., 1*(2), 142-151.

Moghadassi, A.R., Nikkholgh, M.R., Parvizian, F., & Hosseini, S.M. (2010). Estimation of thermophysical properties of dimethyl ether as a commercial refrigerant based on artificial neural networks. *Expert Syst Appl., 37*(12), 7755–7761.
Powell, RL. (2002). CFC Phase-out; have we met the challenge. *J. Fluorine Chem., 114*(2), 237-250.
Reid, R.C., Prausnitz, J.M., & Sherwood, T.K. (1977). *The Properties of Gases and Liquids*. McGraw-Hill: New York.
Sharmas Vali Shaik. & Ashok Babu T.P. (2017). Theoretical Computation of Performance of Sustainable Energy Efficient R22 Alternatives for Residential Air Conditioners. *Energy Procedia., 138*, 710-716.
United Nations Environmental Programme. (1987). Montreal Protocol on substances that deplete the ozone layer, Final act. New York, United Nations.