2012

Investigation of Cubic EOS Models for HFO-1234yf Refrigerant Used In Automotive application

Anant Agrawal
avi_anthony.cornelio@daimler.com

Avi Anthony Cornelio

Dirk Limperich

Investigation of Cubic EOS models for HFO-1234yf Refrigerant Used in Automotive Application

Anant Agrawal[1], Avi A Cornelio[2,*], Dirk Limperich[3]

[1]Mechanical Department, Birla Institute of Technology & Science, Zuarinagar 403726, Goa, India
Phone: +91 7411 519798, E-mail: anantagrawal14@gmail.com

[2]E/E Department, Mercedes Benz R&D India Ltd, Bangalore 560071, Karnataka, India
Phone: +91 80 6768 8304, E-mail: avi_anthony.cornelio@daimler.com

[3]RD/KIT, Daimler AG, Sindelfingen 71059, Germany
Phone: +49 7031 904 3786, E-mail: dirk.limperich@daimler.com

* Corresponding Author

ABSTRACT

The need for a consistent and reliable calculation of thermodynamic property of refrigerants has been a topic of research since the past decade. This paper reports a study of various cubic equations of state (EOS) for a refrigerant to be used in automotive applications. Thermodynamic properties of refrigerant 2,3,3,3-tetrafluoropropene (HFO-1234yf) using three different cubic equations of state, i.e. Peng-Robinson (PR), Yu-Lu (YL) and Guo-Du (GD), are modeled, compared and analyzed. A generic technique applicable to any fluid based on the concept of departure functions is employed. The thermodynamic properties generated using each cubic equation is validated against data from most acceptable NIST-REFPROP database. The PR and YL equations are found to be far more accurate and than Gu-Du equation of state in the operating region of a vehicle. The maximum error in vapor pressure and saturated liquid density is found to be 0.62 % and 0.19 % respectively using co-relations developed by Leck. The maximum error of less than 0.4 % in vapor enthalpy and entropy, using PR and YL equations make them an attractive alternative to NIST tables. The GD method without parameter tuning is not suggested for use through this study. Our studies show that error increases as we move away from the saturated region and maximum around the critical point. We propose an optimal set of simple thermodynamic models for use in vehicular applications. These models are computationally less expensive and hence an advantage. Future work involves using these thermodynamic models at a vehicular level for refrigeration cycle simulation.

1. INTRODUCTION

The increasing concern on global warming demands a replacement of currently used refrigerant - R134a. The refrigerant 2,3,3,3-tetrafluoropropene (HFO-1234yf or R1234yf) is identified as the new low global warming automotive AC refrigerant and will substitute the existing refrigerant. It offers a Global Warming Potential (GWP) of 4, against a GWP of 1430 in case of R134a. It will be used in place of R134a to meet the European regulation - EC Directive 2006/40/EC of a refrigerant not exceeding a GWP of 150. This will also help to acquire the much required US EPA fuel economy credits. In Europe, for all new type approved automobiles starting 2011 the new refrigerant is required. Currently, much of the research and development activity in industry and institutions involve investigation into the property and molecular interaction of R1234yf. Minor and Spartz (2008) evaluated different properties of this new molecule and concluded it as an excellent refrigerant for automotive air conditioning. Meyer (2009) examined experimental and simulated sub-system performance results with the goal of demonstrating minimal hardware modifications within a global platform so that on a single assembly line vehicles can be built to accept either R1234yf or R134a.

Measured thermodynamic properties as well as the amount of published data on R1234yf are very limited. REFPROP (Lemmon *et al*., 2007) tables involve multi parameter equations of state along with large amount of

precise experimental data and fitting to simulate the thermodynamic properties. An accurate and computationally beneficial method is desirable to simulate different thermodynamic properties for the purpose of dynamic simulation of a refrigeration cycle in a ground vehicle. Several researchers have worked towards development of basic thermo physical models to evaluate refrigerant properties. Leck (2009) developed a Martin Hou equation of state model for calculation of thermo physical properties of this new refrigerant. Tanka and Higashi (2009) presented experimental data on critical properties of R1234yf. Brown et al. (2009) estimated the properties of eight fluorinated propene isomers (including R1234yf) using an approximate method that involves the Peng and Robinson (1976) equation of state and standard methods (Poling et al., 2000) for calculating the ideal gas specific heat capacity at constant pressure, the acentric factor and the critical point properties (temperature, pressure and density).

This work aims at modeling the thermodynamic properties (enthalpy, entropy and density) of refrigerant R1234yf using three cubic equations of state, namely Peng-Robinson (PR), Yu-Lu (YL) and Guo-Du (GD) adapted from reference Peng and Robinson (1976), Yu and Lu (1986) and Guo and Du (1989) respectively. The selection of these models is partly based on the work similar to Liangui *et. al* (1995). Using a general *departure function* approach, the behavior of these models are compared and analyzed with the data obtained from the standard NIST-REFPROP (Dec 22nd, 2010) database, which so far have not been explored much in this regard. The explored area is the thermodynamic diagram which include both saturated liquid and vapor, sub cooled liquid and superheated vapor region. Isothermal and isobaric lines in Pressure-Enthalpy (PH) diagram and Temperature-Entropy (TS) diagram respectively are plotted. The errors are also compared and analyzed for each cubic equation. This paper presents an optimal set of thermodynamic models to be applied for vehicular simulation of air conditioning cycle which is both computationally less expensive and also does not require large amount of experimental data.

2. DEPARTURE METHOD

It is often required to estimate the thermodynamic properties (enthalpy and entropy) of refrigerant at any given temperature and pressure. The departure function approach is basically the difference between the real fluid property and the ideal gas property of a given substance at a fixed temperature and pressure. This method utilizes the fact that the changes in these properties i.e. enthalpy and entropy are independent of the path. This also implies that one can choose any convenient path connecting the initial and final states to estimate the change in the property.

The expression for enthalpy at a given temperature and pressure using the departure method can be given by (Rao, 1997):

$$H = (H - H^{ig})_{T,P} + \int_{T_{ref}}^{T} C_p^{ig} dT - (H - H^{ig})_{ref} + H_{ref} \tag{1}$$

Where, $(H - H^{ig})_{T,P}$ represents the difference between the enthalpies of a real fluid and the fluid in the ideal gas state at the same temperature and pressure, and is called the enthalpy departure or residual enthalpy and is given by:

$$(H-H^{ig})_{T,P} = RT(Z-1) + \int_{v=\infty}^{v} \left\{ T\left(\frac{\partial P}{\partial T}\right)_v - P \right\}_T dv \tag{2}$$

Where Z is the compressibility factor for a real gas. In a similar way, the expression for entropy at a given temperature and pressure using the departure method can be given by (Rao, 1997):

$$S = (S - S^{ig})_{T,P} + \int_{T_{ref}}^{T} \frac{C_p^{ig}}{T} dT - R \ln \frac{P}{P_{ref}} - (S - S^{ig})_{ref} + S_{ref} \tag{3}$$

Where, $(S - S^{ig})_{T,P}$ represents the entropy departure or residual entropy and is given by:

$$(S - S^{ig})_{T,P} = R \ln Z + \int_{v=\infty}^{v} \left(\frac{\partial P}{\partial T} - \frac{R}{v} \right) dv \tag{4}$$

3. THERMODYNAMIC MODELS FOR HFO-1234yf

An equation of state is a constitutive equation which provides a mathematical relationship between two or more state functions associated with matter, such as its temperature, pressure, volume, or internal energy. To date, only a few authors have presented EoS for R1234yf in open literature. In particular, Akasaka *et al*. (2010) present both an Extended Corresponding States (ECS) EoS and a Patel-Teja (PT) EoS, Brown *et al*.(2010) present a Peng-Robinson (PR) EoS, Neto, Barbosa (2010) present a PR EoS, and Leck (2009) presents a Martin-Hou (MH) EoS.

3.1 Cubic Equation of State

In this work cubic equation of state has been undertaken for modeling the refrigerant properties because of its advantages like simplicity of application, estimation of few parameters and requirement of low computational effort. The cubic equation of state is a relation of the form *f (P,v,T) = 0*. Furthur, we present three EoS models to study the properties of R1234yf refrigerant.

3.1.1 Peng-Robinson Equation of State

The Peng-Robinson equation of state was proposed by D. Peng, a doctoral student of Prof. D.B. Robinson at the University of Alberta and was first published in the Industrial and Engineering Chemistry: Fundamentals Journal in 1976. In this equation, all parameters of this equation are functions of critical property and acentric factor. This equation also uses different volume dependence in the attraction term of the model. The Peng-Robinson equation is of the following form:

$$P = \frac{RT}{v-b} - \frac{a[T]}{v^2 + 2bv - b^2} \tag{5}$$

The parameters *a* and *b* are defined as:

$$a[T] = 0.45723553\left(\frac{R^2T_c^2}{P_c}\right)\left(1+\left(0.37464+1.54226\omega-0.26992\omega^2\right)\left(1-\sqrt{T_r}\right)\right)^2 \tag{6}$$

$$b = 0.07779607\left(\frac{RT_c}{P_c}\right) \tag{7}$$

This equation is one of the most acceptable cubic EoS for thermodynamic modeling. It is found that the Peng-Robinson equation of state is more accurate for non-polar fluids than for polar fluids, with reasonable accuracy near the critical point.

3.1.2 Yu-Lu Equation of State

The Yu-Lu equation of state was proposed by Yu and Lu (1986). The Yu-Lu equation is a three parameter cubic equation of state and is of the following form**:**

$$P = \frac{RT}{v-b} - \frac{a[T]}{v(v+c)+b(3v+c)} \tag{8}$$

The parameters *a*, *b* and *c* are defined as under:

$$a[T] = \left(0.46863-0.0378304\omega+0.00751969\omega^2\right)\left(\frac{R^2T_c^2}{P_c}\right)\alpha[T_r] \tag{9}$$

$$b = \left(0.0892828-0.0340903\omega-0.00518289\omega^2\right)\left(\frac{RT_c}{P_c}\right) \tag{10}$$

and,

$$c = \left(1.70083+0.648463\omega+0.895926\omega^2-3\right)\left(0.0892828-0.0340903\omega-0.00518289\omega^2\right)\left(\frac{RT_c}{P_c}\right) \tag{11}$$

With

$$\log_{10}\alpha = M(\omega)\left[0.406846 - 0.39244T_r + 0.26507T_r^2\right]\left[1 - T_r\right] \tag{12}$$

$$M(\omega) = 0.406846 + 1.87907\omega - 0.792636\omega^2 + 0.737519\omega^3 \tag{13}$$

This EoS was developed for representation of accurate liquid densities for asymmetric mixtures and showed a better result than PR equation. This equation has only one temperature dependent parameter and others depend on acentric factor as it helps achieving mathematically a balanced distribution of error.

3.1.3 Guo-Du Equation of State:
The Guo-Du equation of state was proposed by Guo and Du (1989). The Guo-Du equation is also a three parameter cubic equation of state and is of the following form:

$$P = \frac{RT}{v - b} - \frac{a[T]}{v(v + c) + c(v - b)} \tag{14}$$

The parameters *a*, *b* and *c* is defined as:

$$a[T] = A_a\left(\frac{R^2T_c^2}{P_c}\right)\left[1 + m\left(1 - T_r^{0.5}\right)\right]^2 \tag{15}$$

$$b = A_b\left(\frac{RT_c}{P_c}\right) \tag{16}$$

and,

$$c = A_c\left(\frac{RT_c}{P_c}\right) \tag{17}$$

Where,

$$A_a = (1 + A_b - C_c)^3 \tag{18}$$

$$A_c = 0.5(1 + A_b - 3C_c) \tag{19}$$

And A_b is smallest positive root of the following cubic equation:

$$2A_b^3 + (3 - 6C_c)A_b^2 + (6A_c^2 - 3C_c + 1)A_b - 2C_c^3 = 0 \tag{20}$$

Where, reduced temperature, $T_r = \frac{T}{T_c}$

In GD equation of state, both the parameters m and C_c are function of the reduced temperature. The value of *m* and C_c is shown in Table 1 and 2. This EoS was developed with objective to calculate more accurate liquid densities of heavy hydrocarbons as an improvement from Peng Robinson and an acceptable PVT calculation was obtained for crude oils without tuning any EOS parameter.

Table 1: Expression for *m* as a function of T_r

T_r	*m*
$T_r \leq 1.0$	$m = m_1(1.177631 - 0.553155T_r + 0.405622T_r^2)$ Where, $m_1 = 0.407290 + 1.461495\omega - 0.233747\omega^2$
$T_r > 1.0$	$m = 0.491987 + 1.285305\omega - 0.685388\omega^2$

Table 2: Value of C_c as a function of T_r

T_r	C_c
T_r <0.8	0.308785
0.8<T_r<1	$0.308785-0.64(0.8-T_r)^2$
1.0<Tr<1.2	$0.308785 – 0.64(T_r -1.2)^2$
T_r>1.2	0.308785

3.2 Saturation Properties of HFO-1234yf

The Martin-Hou Equation of State (MH EoS) is an acceptable thermo physical model to generate saturation property information with sufficient accuracy for refrigeration and air conditioning modeling and design, using only a limited amount of available data. The general form of MH EoS is well known. Leck (2009) developed Martin-Hou equation coefficients and thus a model which is quite sufficient for use to evaluate properties of R1234yf. The vapor pressure relationship is given by (Leck, 2009):

$$\ln P_{sat} = A + \frac{B}{T} + C \ln T + DT + E\left(\frac{F-T}{T}\right)\ln(F-T) \tag{21}$$

$$\frac{1}{P}\frac{dP_{sat}}{dT} = -\frac{B}{T^2} + \frac{C}{T} + D - E\left[\frac{F}{T^2}\ln(F-T) + \frac{1}{T}\right] \tag{22}$$

Where P is in kPa and T is in Kelvin. The constants are presented in Table 3. The saturated liquid mass density correlation is given by (Leck, 2009):

$$\frac{\rho_f}{478.0} = \sum_{i=0}^{4} d_i X^i \tag{23}$$

Where,

$$X = \left(1 - \frac{T}{367.85}\right)^{\frac{1}{3}} - 0.3315471 \tag{24}$$

Where ρ_f is in kg m^{-3} and T is in Kelvin. The constants are presented in Table 4. The ideal gas specific heat capacity correlation is given by (Leck, 2009):

$$c_p^{ig} = \sum_{i=0}^{5} c_i T^i \tag{25}$$

Where c_p^{ig} is in kJ kg^{-1} K^{-1} and T is in K. The constants are presented in Table 5.

Table 3: Constants for Equation (21) & Equation (22)

A	B	C	D	E	F
48.70134	-4054.888	-5.353373	5.632772×10^{-3}	0.2423738	368.7851

Table 4: Constants for Equation (23)

d_0	d_1	d_2	d_3	d_4
1.667131	2.314933	1.032059	0.09413147	-0.8200684

Table 5: Constants for Equation (25)

c_0	c_1	c_2	c_3	c_4	c_5
0.233399	1.82451×10^{-3}	3.51596×10^{-6}	-1.12489×10^{-8}	1.06071×10^{-11}	-3.48283×10^{-15}

3.3 Clausius-Clapeyron Equation

Within the *PH* dome, the width ΔH is calculated at a constant pressure level using the Clausius-Clapeyron equation, using measured vapor pressure and saturated vapor density and liquid density. The enthalpy along the saturated liquid line is determined by subtracting ΔH from the saturated vapor line. Similarly for a TS diagram the entropy along the saturated liquid line is determined by subtracting ΔH from the saturated vapor line at constant temperature. The Clausius-Clapeyron equation is given as under:

$$H_g = H_f + T \frac{dP_{sat}}{dT}(V_g - V_f) \tag{26}$$

$$S_g = S_f + \frac{H_g - H_f}{T} \tag{27}$$

In case of any cubic EoS, given two variables, the third can be solved. So given the pressure and temperature, volume of the refrigerant can be determined using the EoS. However the saturated liquid enthalpy is calculated using Leck (2009) equation. In order to estimate other thermodynamic properties (enthalpy and entropy) of refrigerant at any given temperature and pressure, the departure method approach is used and the corresponding saturated liquid enthalpy and saturated liquid entropy is calculated using the Clausius-Clapeyron equations as discussed above.

4. RESULTS AND DISCUSSION

The final enthalpy and entropy relations were first derived rigorously using the departure function technique. This was done for each cubic EoS selected to study. A *Modelica* based code was developed for all the resulting equations. Modelica is an object oriented programming language. Dymola is used to solve the set of recursive equations. Dymola is a multi engineering modeling and simulation software developed by Dynasim AB. The solution process depends on the initial value given to all variables by the user. Usually, the software makes use of these initial model variables to calculate their magnitude at the end of each time step. In order to obtain several values of the variable at once, they were formulated as arrays. The array size is specified by the user before simulation. After the solver generates the required output variable array, they are imported into MATLAB for plotting and presentation purpose. Thereafter a comparative study was done between the values predicted using these cubic equations and the standard NIST table values for R1234yf.

The vapor pressure and saturated liquid density was calculated using equation's developed by Leck (2009) and a uniform error was obtained in all the three methods. However, errors in saturated vapor density, saturated liquid and vapor enthalpy and entropy are different for each equation as it is dependent on the cubic equation involved in obtaining these values. Table 6 presents a sample of saturated R1234yf data obtained from the three cubic equations of state upon implementation. A majority of the data on the table look similar with negligible deviation from each other. This shows that all the three set of models show a similar trend. In order to validate our models, we used the standard REFPROP database for this purpose. NIST is an excellent and acceptable library for thermodynamic and transport property of fluids.

The maximum deviation obtained in vapor pressure, saturated liquid and vapor density, enthalpy and entropy for all the three equations with respect to the REFPROP (Dec 22nd, 2010) database is tabulated in Table 7. As temperature and pressure increase, the thermodynamic properties prediction with the cubic equations tends to deviate much from the experimental values. The maximum deviation in the vapor enthalpy in both the PR and YL is 0.39 % however in case of GD it is found to be 1.88%. The maximum deviation in the vapor entropy in PR is 0.26%, YL is 0.39 % and in case of GD it is found to be 2.3%. Figure 1, 3 and 5 shows the P-h diagram for refrigerant R1234yf generated using the cubic equation PR, YL and GD respectively along with the reference RefPROP data. Figure 2, 4 and 6 shows the T-S diagram for the refrigerant R1234yf generated using the cubic equation PR, YL and GD respectively along with the reference RefPROP data. The maximum deviation in the properties is found near the critical point. The reason for this abrupt behavior near the critical point has been well explained by Wilhelm and Letcher, 2010.

Table 6: Properties of R1234yf refrigerant at saturation conditions

	Temperature (K)	Pressure (kPa)	Density (kg/m³)	Density (kg/m³)	Enthalpy (kJ/kg)	Enthalpy (kJ/kg)	Entropy (kJ/kg-K)	Entropy (kJ/kg-K)
PR	268	262.584	1193.23	14.6037	189.676	358.499	0.962918	1.59286
	273	312.43	1178.07	17.2666	195.994	361.831	0.986119	1.59358
	283	433.583	1146.33	23.7765	209.063	368.361	1.03275	1.59564
	293	587.437	1112.41	32.1908	222.72	374.648	1.0797	1.59822
	303	779.113	1075.85	43.0077	236.977	380.604	1.12695	1.60097
	313	1013.98	1036.01	56.9134	251.856	386.114	1.17454	1.60348
	323	1297.69	991.947	74.9123	267.398	391.018	1.22253	1.60526
	333	1636.38	942.078	98.598	283.679	395.074	1.2711	1.60562
	343	2036.96	883.517	130.816	300.87	397.859	1.32066	1.60342
	353	2508.11	809.677	177.762	319.402	398.476	1.3723	1.59631
	363	3063.73	695.839	260.895	341.094	393.85	1.43081	1.57614
	367.85	3374.88	477.871	477.871	367.331	367.331	1.50107	1.50107
YL	268	262.584	1193.23	14.6044	189.682	358.496	0.961767	1.59167
	273	312.43	1178.07	17.2681	196.01	361.832	0.985007	1.59241
	283	433.583	1146.33	23.7816	209.104	368.367	1.03173	1.5945
	293	587.437	1112.41	32.204	222.79	374.655	1.07878	1.59709
	303	779.113	1075.85	43.0378	237.077	380.6	1.12613	1.59981
	313	1013.98	1036.01	56.9768	251.979	386.079	1.17379	1.60223
	323	1297.69	991.947	75.038	267.52	390.917	1.22178	1.60382
	333	1636.38	942.078	98.8363	283.757	394.852	1.27022	1.60383
	343	2036.96	883.517	131.253	300.82	397.429	1.3194	1.60106
	353	2508.11	809.677	178.545	319.065	397.694	1.37022	1.59297
	363	3063.73	695.839	262.145	340.099	392.452	1.42689	1.57112
	367.85	3374.88	477.871	477.871	364.796	364.796	1.49296	1.49296
GD	268	262.584	1193.23	14.9492	193.194	358.067	0.974777	1.58997
	273	312.43	1178.07	17.7366	199.777	361.154	0.998955	1.59008
	283	433.583	1146.33	24.6212	213.372	367.089	1.04748	1.59065
	293	587.437	1112.41	33.6567	227.5	372.614	1.09606	1.59133
	303	779.113	1075.85	45.4596	242.065	377.623	1.14435	1.59173
	313	1013.98	1036.01	60.8295	256.917	382.029	1.19182	1.59154
	323	1297.69	991.947	80.7918	271.85	385.74	1.23785	1.59045
	333	1636.38	942.078	106.501	286.559	388.721	1.28159	1.58838
	343	2036.96	883.517	138.794	300.672	391.116	1.32203	1.58572
	353	2508.11	809.677	177.372	314.063	393.36	1.35899	1.58363
	363	3063.73	695.839	221.132	328.007	395.939	1.39612	1.58326
	367.85	3374.88	477.871	477.871	346.704	346.704	1.44599	1.44599

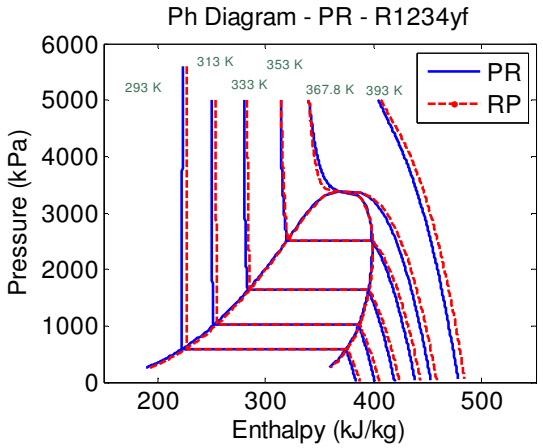

Figure 1: P-h plot of R1234yf generated using PR eq.

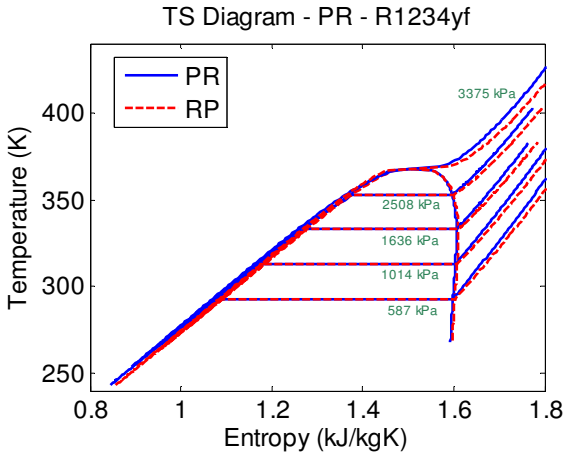

Figure 2: T-S plot of R1234yf generated using PR eq.

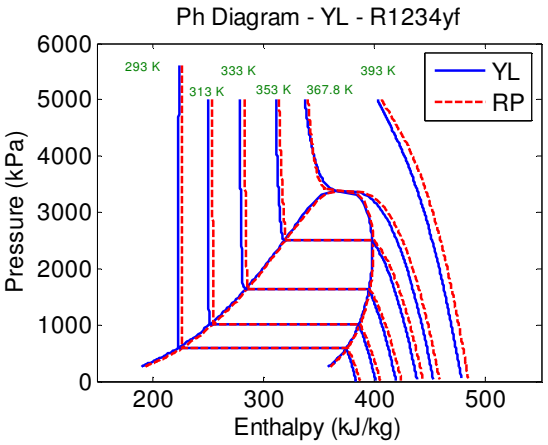

Figure 3: P-h plot of R1234yf generated using YL eq.

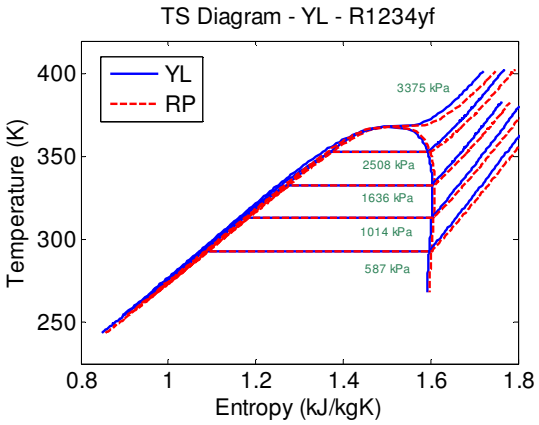

Figure 4: T-S plot of R1234yf generated using YL eq.

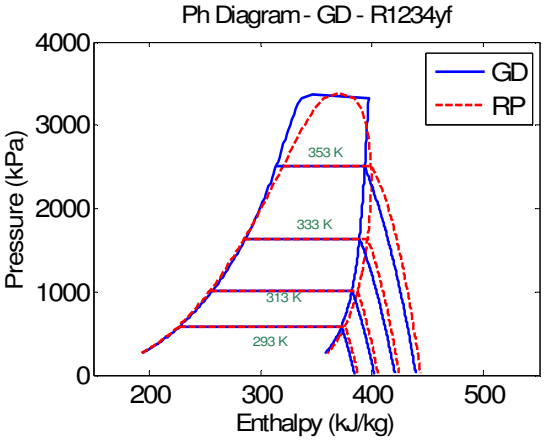

Figure 5: P-h plot of R1234yf generated using GD eq.

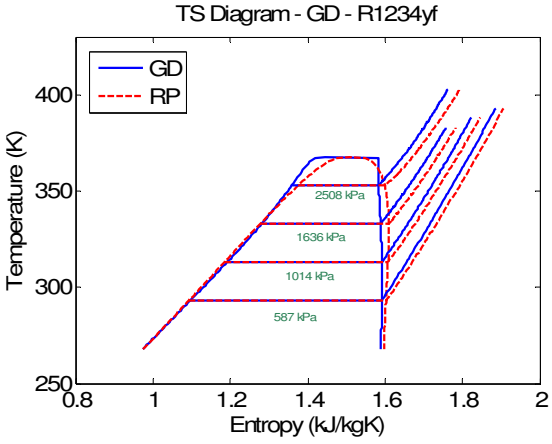

Figure 6: T-S plot of R1234yf generated using GD eq.

Table 7: Comparative study of deviation in three cubic equations

	Max Deviation PR (%)	Max Deviation YL (%)	Max Deviation GD (%)
Vapor Pressure	0.62	0.62	0.62
Liquid Density	0.19	0.19	0.19
Vapor Density	5.5	5.53	32.0
Liquid Enthalpy	1.92	1.92	5.64
Vapor Enthalpy	0.39	0.39	1.88
Liquid Entropy	1.32	1.43	3.75
Vapor Entropy	0.26	0.39	2.3

5. CONCLUSIONS

In this work, we investigated cubic EOS models for HFO-1234yf refrigerant. An accurate and computationally beneficial method was desirable to simulate different thermodynamic properties for the purpose of dynamic simulation of a refrigeration cycle in a ground vehicle. Three cubic equations of state, namely Peng-Robinson (PR), Yu-Lu (YL) and Guo-Du (GD) were used for this purpose. The thermodynamic data were generated using departure function approach for each cubic equation of states. The PR and YL equation showed similar trend and were found to be quite in confirmation with the standard REFPROP values. Thus, either of these equations can be used as an alternate model during dynamic simulations of the refrigeration cycles in automotive applications. Based on this selection, a study similar to Meyer (2009) on system performance of refrigerants in vehicle can be performed. The GD equation although was accurate in low temperature region, showed tremendous deviation from the experimental values as it approached critical region. Thus this model is not suggested for further exploration without parameter tuning. For the operating region of a vehicular refrigeration cycle the errors are well within the acceptable zone. Since the cubic equations are used to compute these properties as against the multi-parameter equation and curve fitting techniques of REFPROP, the computation time in this approach was significantly less, making this method an efficient and fast alternative to simulate the air conditioning cycle of automotives. Future work involves using the developed equations in Dymola for the transient simulations of a vehicular refrigeration cycles.

NOMENCLATURE

P	Pressure	(kPa)
T	Temperature	(K)
v	Molar volume	(m^3 mol^{-1})
R	Universal Gas Constant	(8.314472 kJ $kmol^{-1}$ K^{-1})

Greek Symbols

ρ	Density	(Kg m^{-3})
ω	Acentric Factor	(-)

Abbreviation

NIST	National Institute of Standards and Technology
GWP	Global Warming Potential
EoS	Equation of State

Subscripts

ig	Ideal Gas

Superscripts

c	Critical property
r	Reduced property
f	Saturated liquid
g	Saturated vapor
fg	difference (f-g)
ref	Reference state
sat	Saturation

REFERENCES

Akasaka, R., Tanaka, K., Higashi, Y., 2010, Thermodynamic property modeling for 2,3,3,3-tetrafluoropropene (HFO-1234yf), Int. J. Refrig., vol 33, no. 1: p. 52-60.

Brown, J.S., Zilio, C., Cavallini, A.,2010, Thermodynamic properties of eight fluorinated olefins, *Int. J. Refrig*., vol. 33, no. 2: p. 235-241.

Guo, T.M., Du, L., 1989, A three-parameter cubic equation of state for reservoir fluids, *Fluid Phase Equilibria*, vol. 5, no. 1: p. 47-51.

Leck, T.J., 2009, "Evaluation of HFO-1234yf as a potential replacement for R-134a in refrigeration applications", 3rd IIR Conference on Thermophysical Properties and Transfer Processes of Refrigerants, Paper No. IIR-155, Boulder, Colorado: p. 1-9.

Lemmon, E.W., Huber M.L., McLinden, M.O., 2007, NIST Reference Fluid Thermodynamic and Transport Properties-REFPROP, *NIST Standard Reference Database 23-Version 8.0*.

Liangui, D., Wenchuan, W., Danxing, Z., Jufu, F., 1995, Optimization of the compositions for CFC alternative mixture refrigerants, *Chin. J. Chem. Eng.*, vol. 3, no. 1: p. 32-38.

Meyer, John J., 2009, Production Solutions for Utilization of Both R1234yf and R134a in a Single Global Platform, SAE international

Minor, B., Spatz, M., 2008, HFO-1234yf Low GWP Refrigerant Update, *Proc. 12th Int. Refrig. and Air Cond.Conf. at Purdue*, West Lafayette, Indiana.

Neto, M.A.M., Barbosa, J.R., 2010, Modeling of State and Thermodynamic Cycle Properties of HFO-1234yf Using a Cubic Equation of State, *J. of the Braz. Soc. of Mech. Sci. & Eng.*, vol. 22, no. 5: p.461-467.

Peng, D.Y., Robinson, D.B., 1976, A new two-constant equation of state, *Industrial and Engineering Chemistry: Fundamentals*, vol. 15, no. 1: p. 59-64.

Poling, B.E., Prausnitz, J.M., O'Connell, J.P., 2000, *The Properties of Gases and Liquids", 5th ed,* McGraw-Hill, NY: p. 4.1-4.44.

Rao, Y.V.C., 1997, Thermodynamic Properties of Real Gases, Chapter 8, *Chemical Engineering Thermodynamics*, Universities Press (India) Pvt. Ltd., Hyderabad: p. 269-275.

Tanaka, K., Higashi, Y., 2010, Thermodynamic Properties of HFO-1234yf (2,3,3,3-Tetrafluoropropene), *Int. J. Refrig*., vol. 33, no. 3: p. 474-479.

Wilhelm, E., Letcher, T., 2010, *Heat Capacities: Liquids, Solutions and Vapours*, The Royal Society of Chemistry, Cambridge, p. 314-315.

Yu, J.M., Lu, B.C.Y., 1987, A three-parameter cubic equation of state for asymmetric mixture density calculations, *Fluid Phase Equilibria*, vol. 34, no. 1: p. 1-19.

ACKNOWLEDGEMENT

The authors would like to thank the unknown reviewer for his constructive comments. The colleagues at Sindelfingen and Bangalore are credited towards the formulation of this article. The support of Electrical and Electronics Department at MBRDI and Climate Control Department at Daimler AG is gratefully acknowledged.