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Modeling of Thermodynamic Properties for Pure Refrigerants and Refrigerant Mixtures by Using the Helmholtz Equation of State and Cubic Spline Curve Fitting Method

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Abstract When simulating refrigeration systems or equipment, knowledge of refrigerant thermodynamic properties is required. While some of the refrigerants are made of pure fluids, some of these refrigerants are made by mixing of two or more pure refrigerants with the predetermined percentages. Properties of refrigerants are a major part of international trade, therefore, it is a subject of interest of international standards. In this study a computer model was developed based on Helmholtz equation of state and cubic spline curve fitting models developed by using saturation thermophysical properties of the refrigerants and refrigerant mixtures. Java programming language was used to model equation of state. As an example the equations for R1234yf and R410A were presented in this paper. With the new model, thermodynamic properties of R1234yf and R410A were compared with REFPROP 9.0. It shows that the total mean deviations of the new model are less than 0.5%.

Keywords Refrigerants, Thermodynamic Properties, Equation of State, Calculation, R1234yf, R410A

1. Introduction

Refrigeration systems become more important for people's daily lives in recent decades, and more refrigeration products are designed every year, which requires the design of refrigeration products to be more efficient. One of the effective ways to improve the design efficiency for refrigeration products is to use the computer simulations. With the computer simulation methods, models of different components of the refrigeration products to be simulated must be built, and the models for thermodynamic properties of refrigerants are very important and indispensable one.

Accurate knowledge of thermodynamic properties is of great importance in the design of refrigeration equipment. Since it is not possible to measure every refrigerant property of interest at every combination of temperature and pressure, refrigerant properties are usually determined with some sort of mathematical model. According to McLinden et al. [20], a properly formulated equation of state was capable of reproducing experimental property data within the experimental uncertainty of the data and also yields through integration and differentiation, all of the thermodynamic properties of interest. Even though there are number of equations of state models that have the abilities mentioned, these formulations present the disadvantage of their low computational speed and that most of the thermodynamic properties equations are implicit and require more iterations. The traditional methods based on equation of state cannot meet such requirement because of unavoidable iterations in calculation. But, calculations of thermal properties of refrigerants are desired to be very fast, accurate and stable in cases of simulation of refrigeration system, etc. Therefore, the engineering calculation and simulation of refrigeration systems require the availability of simple and efficient mathematical models for the determination of thermodynamic properties of refrigerants.

When simulating refrigeration systems or equipment, the thermodynamic properties have to be determined a large number of times and sometimes their calculation is required within iteration loops. Clear examples are dynamic simulation of refrigeration systems or finite element analyses of refrigeration equipment. Therefore, in order to improve the computation stability, different authors presented explicit or hybrid formulations for several pure and mixture refrigerants (Chan et al.[2], Chartes et al.[3],Cleland et al. [4,5],Devotta et al.[6], Ding et al.[7], Fernandes et al.[9],Huber et al.[11]).

In the works of Ding et al. [7,8], implicit equations were proposed to calculate different kinds of thermal properties.

The coefficients of the implicit equations were determined by curve-fitting methods, using REFPROP 6.0 to generate the source data. The highest variable order of the polynomial of the implicit equations that they were used, so explicit formulae for the different variables could be obtained.

Recently, intelligent some computer models for calculating thermodynamic properties of refrigerants have been improved. Akasaka et al. [1] presented a timely and reliable equation of state for 2, 3, 3, 3-tetrafluoropropane (HFO-1234yf). They used Patel Teja equation of state and the extended corresponding state(ECS) model have been individually applied to property modeling for this refrigerant. Tanaka et.al.[29] measured thermodynamic properties of HFO-1234yf. Especially, they measured critical temperature, critical density and critical pressure with the visual observation of the meniscus disappearance and they determined to be 367,85 K, 478 kg*m^{-3} and 3382 kPa respectively. They used Peng-Robinson Equation for based on the critical parameters. Richter et.al. [22] measured p- ρ -T behavior of 2,3,3,3- tetrafluoroprop-1-ene (R1234yf) from T= (232 to 400) K with pressures up to 10 MPa using a two-sinker densimeter, extend from low-density vapor to compressed-liquid states and include the extended critical region. They used Helmholtz energy equations for calculation of thermodynamic properties of R1234yf. Monte et.al. [21] developed of the thermodynamic properties of two mixtures of hydrofluorocarbon (HFC) refrigerants,i.e. R407C and R410A(in the superheated vapor state)was carried out. He used Martin-Hou equation of state for the calculation. Sozen et.al.[25] determinated thermodynamic properties of an alternative refrigerant (R407C) using artifical neural network. Froba et.al.[10] measured thermophysical properties of the refrigerant mixtures R410A and R407C using dynamic light scattering.

Helmholtz free energy mixing law has been recognized as the best mixing law until now. Lemmon and Tillner-Roth [15] and Lemmon and Jacobsen [16] applied it to the thermo physical properties estimation of mixture R32 /R125/R134a with an absolute average deviation within 0,3%.

Küçüksille et al.[13] used Data Mining for the determination of thermodynamic properties as enthalpy, entropy, specific volume values for any temperature and pressure of alternative refrigerants. The method proposed offered more flexibility, and therefore thermodynamic simulation of vapor compression refrigeration systems was fairly simplified. Saleh et al. [23] used BACKONE equations to screening of pure fluids as alternative refrigerants. The coefficients of the implicit equations were determined by curve-fitting method, using REFPROP 7.1 to generate to source data.

Sieres et al. [24] used a hybrid formulation for the calculation of thermodynamic properties of pure refrigerants and refrigerant mixtures. Implicit polynomial equations of order three were used for curve fitting of the main thermodynamic properties. Then, explicit formulae for the related properties were obtained. The formulation was similar to that of Ding and co-workers, though some differences existed in the transformation of the thermodynamic properties before the regression analysis was performed near the critical point in the mathematical treatment. Mahajan et al. [18] presented a new predictive method for estimation of accurate thermodynamic properties of the liquid-vapor coexistence states. Calculated values of vapor pressure and saturated liquid density for argon, nitrogen, ethylene, oxygen, fluorine, methane, dichlorodifluoromethane (R12) and propane were used to demonstrate the method. Zhao et al. [32] presented the implicit curve-fitting method for fast and stable calculations of thermodynamic properties of subcritical refrigerants, and used it at the saturated liquid or vapor state as the reference state. With the new method, thermodynamic properties of supercritical CO_2 and R410A were predicted and compared with REFPROP 8.0.

Mathematical expressions for the derivatives of the residual Helmholtz energy were presented elsewhere(Akasaka et al.[1], Richter et al.[22]). From the derivatives, all thermodynamic properties of the fluid of interest could have derived. The literature summarized the relation between common thermodynamic properties and the derivatives of the Helmholtz energy, e.g., Lemmon and Jacobsen [17], Span [26] and Tillner-Roth et al. [30]. According to Tillner-Roth et al. [31] Helmholtz energy model could have represented a system with the highest accuracy using the fewest coefficients. However, it was specific to the R32/ 134a system and could not have extended to ternary systems using the current functional form.

In this study, in order to calculate accurately thermodynamic properties as an enthalpy, entropy, internal energy, specific volume, density, quality values for any temperature and pressure of pure refrigerants, a new computer program was developed. This model was obtained for the base of ISO 17584 Helmholtz equation of state (*HEoS*) and cubic spline curve fitting method (*CSCFM*). In this study, one of these methods (*HEoS*) was used to calculate the thermodynamic properties in subcooled liquid and superheated vapor phases, and the other (*CSCFM*) to calculate the thermodynamic properties in saturated liquid – vapor phases. The objective was to have these methods that meet the following requirements: accurate and stable computation of thermal properties; Helmholtz equations and cubic spline curve fitting equations, so iterative numerical methods were not required; reversibility of these equations, so the calculation of the related parameters from different Helmholtz and curve fitting formulas were reversible; same format of the all equations used, so the method could have been easily programmed and adjusted to multiple refrigerants.

Although many works related with the thermodynamic properties of some refrigerants and refrigerant mixtures have taken place in the literature until now, there was a limited data for these refrigerants. Therefore, as an example, the

equations for R1234yf and R410A refrigerants were presented in this paper and also thermodynamic properties of these refrigerants based on three phases were calculated in the developed program. The results for these refrigerants were obtained from the REFPROP 9.0 as a supplementary data to compare with the developed program.

2. Calculation Methods

In this paper, we utilized two methods for calculating of refrigerants thermodynamic properties. These are International ISO17584 Helmholtz Equation of State (*HEoS*) and Cubic spline curve fitting method (*CSCFM*). The first method (*HEoS*) was used for calculating thermodynamic properties in subcooled and superheated regions and the other (*CSCFM*) was used for calculating thermodynamic properties at saturated liquid, saturated vapor lines and in saturated liquid-vapor mixed region.

2.1. International ISO17584 Helmholtz Equation of State

International Standard specifies thermo physical properties of several commonly used refrigerants. This international standard is applicable to the refrigerants R12, R22, R32, R123, R125, R134a, R143a, R152a, R717 (ammonia) and R744 (carbon dioxide) and to the refrigerant blends R404A, R407C, R410A and R507A [12]. Richter et.al. [22] measured thermodynamic properties of R1234yf using Helmholtz energy as the fundamental property with independent variables of density and temperature. The fit started with the "short form" equation of state of Span and Wagner[27].The equations is similar to international standard equations. The following properties are included: density, pressure, internal energy, enthalpy, entropy, in both single- phase states (sub cooled and superheated) and along the liquid-vapor saturation boundary. An equation of state for a pure fluid may express the reduced molar Helmholtz energy, A, as a function of temperature and density. The equation was composed of separate terms arising from ideal-gas behavior (subscript"*id*") and a "residual" or "real-fluid" (subscript "*r*") contribution as given in Equation (2.1):

$$\phi = \frac{A}{RT} = \phi_{id}(\rho,T) + \phi_r(\rho,T) \tag{2.1}$$

Where R is a gas constant. The "residual" or "real-fluid" contribution was given by Equation (2.2):

$$\phi_r = \sum_k N_k \tau^{t_k} \delta^{d_k} \exp\left[-\alpha_k(\delta-\varepsilon_k)^{l_k}\right]\exp\left[-\beta_k(\tau-\gamma_k)^{m_k}\right] \tag{2.2}$$

This equation for R1234yf was given in (2.2.a);

$$\phi_r = \sum_{k=1}^{5} N_k \tau^{tk} \delta^{dk} + \sum_{k=6}^{10} N_k \tau^{tk} \delta^{dk} \exp(-\delta^{lk}) + \sum_{k=11}^{15} N_k \tau^{tk} \delta^{dk} \exp[-\alpha_k(\delta-\varepsilon_k)^2 - \beta_k(\tau-\gamma_k)^2] \tag{2.2.a}$$

The ideal-gas contribution can be represented in one of several ways. One representation was in terms of the heat capacity of the ideal-gas state, as given in Equation (2.3):

$$\phi_{id} = \frac{h_{ref}}{RT} - \frac{s_{ref}}{R} - 1 + \ln\left(\frac{RT\rho}{P_{ref}}\right) + \frac{1}{RT}\int_{T_{ref}} C_{p,id}\,dT - \frac{1}{R}\int_{T_{ref}}^{T} \frac{C_{p,id}}{T}dT \tag{2.3}$$

Where h_{ref}, is the arbitrary reference enthalpy for the ideal gas at the reference state specified by T_{ref} and s_{ref}, is the arbitrary reference entropy for the ideal gas at the reference state specified by T_{ref}.

The heat capacity of the ideal gas state, $C_{p,id}$ was represented as a function of temperature by the general form consisting of separate summations of polynomial (empirical) and exponential (theoretical) terms, as given in Equation (2.4):

$$\frac{C_{p,id}}{R} = c_0 + \sum_k c_k T^{t_k} + \sum_k a_k \frac{u_k^2 \exp(u_k)}{[\exp(u_k)-1]^2} \tag{2.4}$$

Where,

$$u_k = \frac{bk}{T} \tag{2.5}$$

A second representation of the ideal-gas contribution was given directly in terms of the Helmholtz free energy, as shown in Equation (2.6):

$$\phi_{id} = f_1 + \frac{f_2}{T} + \ln(\rho) + (1-C_0)\ln(T) - \sum_k C_k\left(\frac{1}{t_k+1}\right)\left(\frac{1}{t_k}\right)T^{t_k} + \sum_k a_k \ln\left(1-\exp\left(\frac{b_k}{T}\right)\right) \tag{2.6}$$

This equation for R1234yf was given in 2.6.a;

$$\phi_{id} = f_1 + f_2\tau + \ln\delta + 4.944\ln\tau + \sum_{k=1}^{4} v_k \ln\left[1-\exp\left(-\frac{u_k\tau}{Tc}\right)\right] \tag{2.6.a}$$

Where;

f_1, f_2, C_0, C_k, a_k, b_k, t_k, u_k, v_k are either empirical or theoretical parameters.

Thermodynamic properties of mixtures are calculated by applying mixing rules to the Helmholtz energy of the mixture components together with a separate mixture function. The reduced Helmholtz energy of the mixture is a sum of ideal-gas and residual contributions as given by Equation (2.7):

$$\phi_{mix} = \frac{A}{RT} = \phi_{mix,id}(\rho,T) + \phi_{mix,r}(\rho,T) \quad (2.7)$$

The ideal gas part was given by equation (2.8);

$$\phi_{mix,id} = \sum_{i=1}^{n}(x_i\phi_{i,id} + x_i \ln x_i) + f_3 + f_4/T \quad (2.8)$$

f_3, f_4 are either empirical or theoretical parameters.

The residual part was given by equation (2.9);

$$\phi_{mix,r} = \sum_{i=1}^{n} x_i\phi_{i,r} + \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} x_i x_j \phi_{ij,excess} \quad (2.9)$$

The first summation in this equation represents the ideal solution; it consists of the real fluid terms for each of the pure fluids multiplied by their respective compositions. The double summation accounts for the "excess" Helmholtz energy or "departure" from ideal solution. The $\varphi_{i,r}$ and $\varphi_{ij,excess}$ functions in Equation (2.9) are not evaluated at the temperature, T_{mix}, and density, ρ_{mix}, of the mixture, but, rather, at a reduced temperature, τ and density, δ. The mixing rules for the reducing parameters are given by Equations (2.10) and (2.11):

$$\tau = \frac{T^*}{T_{mix}} \quad (2.10)$$

where;

$$T^* = \sum_{i=1}^{n} x_i T_i^* + \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} x_i x_j \zeta_{ij}$$

$$\delta = \frac{\rho_{mix}}{\rho^*} \quad (2.11)$$

where;

$$\frac{1}{\rho^*} = \sum_{i=1}^{n} \frac{x_i}{\rho_i^*} + \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} x_i x_j \xi_{ij}$$

The $\varphi_{ij,excess}$ function is of the general form of equation (2.12);

$$\varphi_{ij,excess} = F_{ij}\sum_k N_k \delta^{dk}\tau^{tk}\exp(-\delta^{lk}) \quad (2.12)$$

Starting with an equation of state explicit in reduced Helmholtz energy for pure fluids, e.g. Equations (2.1) to (2.6), the thermodynamic properties were given by the following; [12]

$$P = RT\rho\left(1 + \delta\frac{\partial\phi_r}{\partial\delta}\right) \quad (2.13)$$

$$u = RT\left(\tau\frac{\partial\phi_{id}}{\partial\tau} + \tau\frac{\partial\phi_r}{\partial\tau}\right) \quad (2.14)$$

$$h = RT\left(1 + \tau\frac{\partial\phi_{id}}{\partial\tau} + \tau\frac{\partial\phi_r}{\partial\tau} + \delta\frac{\partial\phi_r}{\partial\delta}\right) \quad (2.15)$$

$$s = R\left(-(\phi_{id} + \phi_r) + \tau\frac{\partial\phi_{id}}{\partial\tau} + \tau\frac{\partial\phi_r}{\partial\tau}\right) \quad (2.16)$$

$$g = RT\left(1 + \phi_{id} + \phi_r + \delta\frac{\partial\phi_r}{\partial\delta}\right) \quad (2.17)$$

$$C_v = R\left(-\tau^2\frac{\partial^2\phi_{id}}{\partial\tau^2} - \tau^2\frac{\partial^2\phi_r}{\partial\tau^2}\right) \quad (2.18)$$

$$C_p = C_v + R\frac{\left(1 + \delta\frac{\partial\phi_r}{\partial\delta} - \delta\tau^2\frac{\partial^2\phi_r}{\partial\tau\partial\delta}\right)}{1 + 2\delta\frac{\partial\phi_r}{\partial\delta} + \delta^2\frac{\partial^2\phi_r}{\partial\delta^2}} \quad (2.19)$$

Starting with the mixture equation of state explicit in reduced Helmholtz energy, Equations (2.7) to (2.12), the thermodynamic properties of mixtures are given by the same expressions as for pure fluids [Equations (2.13) to (2.19)], except that the derivatives of the residual part are composed of contributions from the pure components and the excess function.

As it is seen from that the equation Helmholtz free energy type of equation of states were required only derivatives to obtain properties, therefore they were easier to simulate in computer programs compare to pressure type of equation of states.

Saturated regions equations can be obtained equation of state;

$$P(\tau,\delta_{liq}) = P(\tau,\delta_{vap.}) \quad (2.20)$$

$$g(\tau,\delta_{liq.}) = g(\tau,\delta_{vap.}) \quad (2.21)$$

As mentioned by Ding et al. [8], for most of refrigeration applications, the subcooling of refrigerants are limited, so the following formulae can be used for linking the temperature, enthalpy and entropy of a sub cooled liquid when the pressure P (or the saturation temperature) was given as an input parameter:

$$h = h_{ls} - C_{pls}(T_{ls} - T) \quad (2.22)$$

$$s = s_{ls} - C_{pls}(T_{ls}/T) \quad (2.23)$$

The variables h_{ls}, s_{ls} and Cp_{ls} represent saturated liquid thermal properties for saturated pressure (P_{sat}), which were calculated from Helmholtz equations in section 2.1.

2.2. Cubic Spline Curve Fitting Method

Cubic spline curve fitting method was used in transforming the saturation data into the curves for the calculation of the thermodynamic properties in the saturation region. If the cubic spline function was given in this form;

$$s_k(x) = a_k(x - x_k) + b_k(x_{k+1} - x) + [c_{k+1}(x - x_k)^3 + + c_k(x_{k+1} - x)^3]/(6h_k) \quad 1 \le k \le n \tag{2.24}$$

the derivative equations were given below:

$$s_k'(x) = a_k - b_k + [c_{k+1}(x - x_k)^2 - c_k(x_{k+1} - x)^2]/(2h_k) \quad 1 \le k \le n \tag{2.25}$$

$$s_k''(x) = [c_{k+1}(x - x_k) + c_k(x_{k+1} - x)]/(h_k) \quad 1 \le k \le n \tag{2.26}$$

Here c_k can be written as a function of a_k and b_k.

$$b_k=[6y_k-h_kc_k]/(6h_k), \ 1 \le k \le n \tag{2.27}$$

$$a_k=[6y_{k+1}-h_k^2c_{k+1}]/(6h_k), \ 1 \le k \le n \tag{2.28}$$

In this case, the system of equation to be solved was converted into terms involving only c_k.

$$h_{k-1}c_{k-1}+ 2(h_{k-1}- h_k)c_k+ h_k c_{k+1}= 6\left[\frac{y_{k+1}-y_k}{h_k} - \frac{y_k-y_{k-1}}{h_{k-1}}\right], \ 1 \le k \le n \tag{2.29}$$

In this system, there are totally n-2 equations;

$$w_k = \frac{y_{k+1}-y_k}{h_k}, \ 1 \le k \le n \tag{2.30}$$

If the above definition is given, the following matrix form will be taken to solve the equation system:

$$\begin{bmatrix} 1 & 0 & 0 & \dots & 0 & 0 & 0 \\ h_1 & 2(h_1+h_2) & h_2 & \dots & 0 & 0 & 0 \\ 0 & h_2 & 2(h_2+h_3) & \dots & 0 & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \dots & 2(h_{n-3}+h_{n-2}) & h_{n-2} & 0 \\ 0 & 0 & 0 & \dots & h_{n-2} & 2(h_{n-2}+h_{n-1}) & h_{n-1} \\ 0 & 0 & 0 & \dots & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c_0 \\ c_1 \\ c_2 \\ \dots \\ c_{n-2} \\ c_{n-1} \\ c_n \end{bmatrix} = \begin{bmatrix} A \\ 6(w_2-w_1) \\ 6(w_3-w_2) \\ \dots \\ 6(w_{n-2}-w_{n-3}) \\ 6(w_{n-1}-w_{n-2}) \\ B \end{bmatrix} \tag{2.31}$$

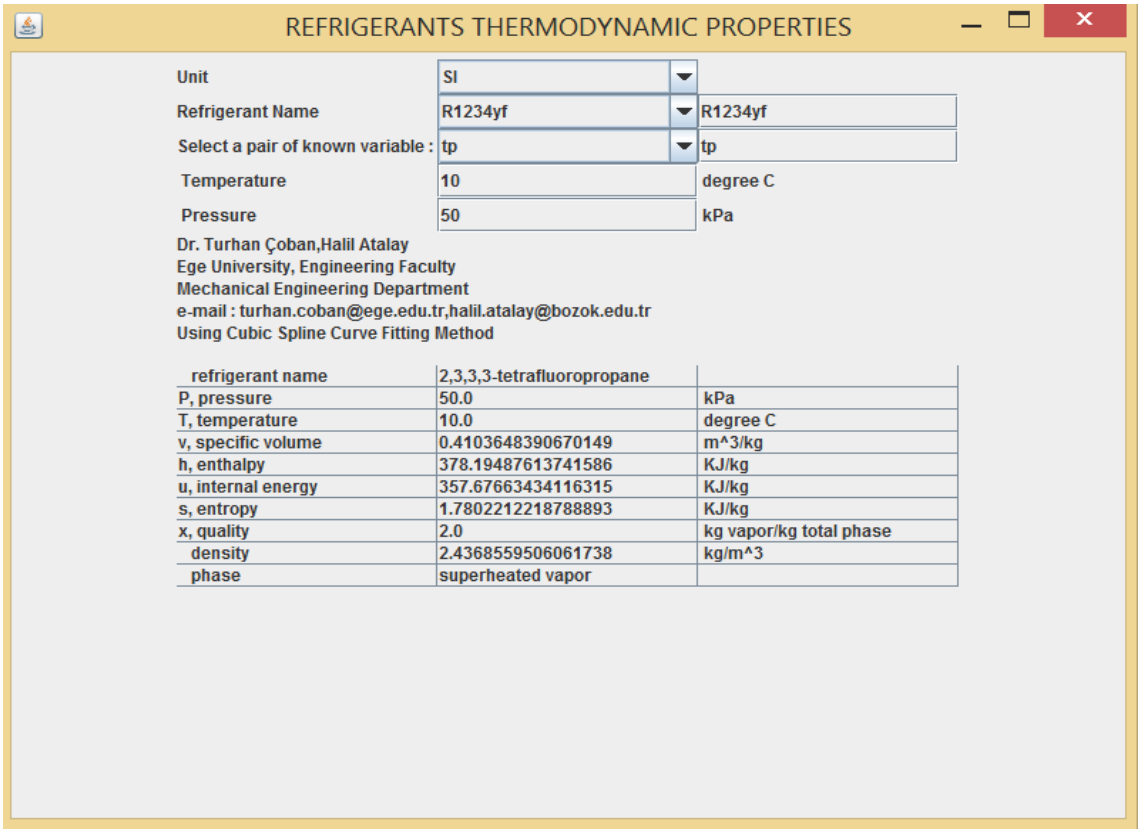
Here, A and B are the boundary conditions for the second derivative which should be defined by the user. In our model, A and B is taken as zero (natural cubic spline). This system of equation constitutes a practical system as it has a small margin of error when it is solved for the chart data.

3. Description of Developed Computer Program

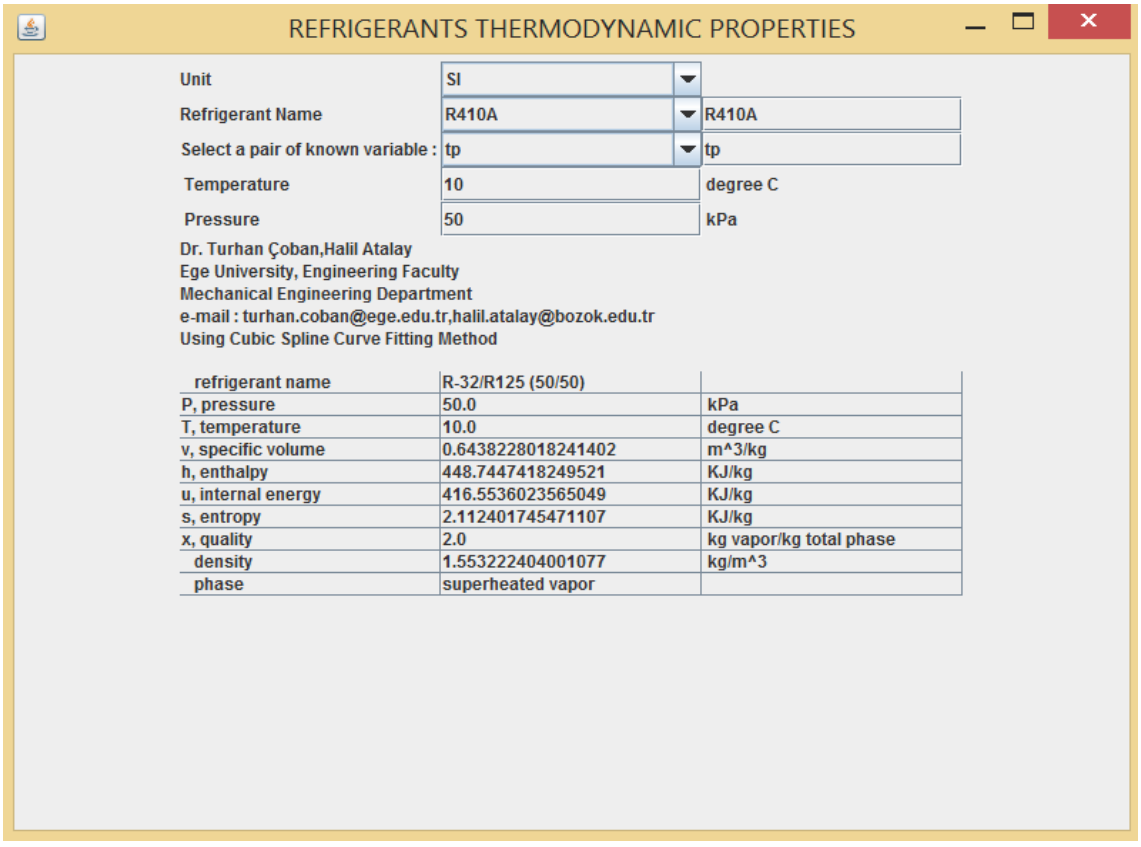
In order to evaluate thermodynamic properties of refrigerants by using equations given in section 2, a new computer program (refrigerant) was developed on a java computer program language. Thermodynamic properties in subcooled and superheated regions were designed in java class "RefISO17584" by using Helmholtz Equation of state [12]. Also, thermodynamic properties of refrigerant on the saturation liquid, saturation vapor lines and in the saturation liquid-vapor phase were designed in java class "ref_CS3" by using cubic spline curve fitting method directly taken from the ASHRAE [28]. Thermodynamic properties were defined as a temperature, pressure, enthalpy, entropy, internal energy, density, specific volume, quality of pure refrigerants, etc. Computer simulation code should be able to work with any two pair of known thermodynamic properties as input parameters. Simulation program includes sets of root solving methods to obtain solutions of *EOS* for different thermodynamic input pairs. The thermodynamic known property sets in the model is as follows: ***tx*,** Temperature- Quality; ***tp*** or ***pt***, Temperature- Pressure; ***tv*** or ***vt*,** Temperature- Specific Volume; ***th*,** Temperature- Enthalpy; ***tu*,** Temperature- Internal Energy; ***ts*,** Temperature- Entropy; ***pv*** or ***vp*,** Pressure- Specific Volume; ***ph*,** Pressure- Enthalpy; ***pu*,** Pressure- Internal Energy; ***ps*,** Pressure- Entropy; ***px*,** Pressure- Quality. In order to use the thermodynamic properties in a java program, a code similar to following should be called:

refrigerant st=new refrigerant ("R1234yf");
double temperature=10,0;
double pressure =50,0;
double a[]=st. property("*tp*", temperature, pressure).

If the above code is called in a program, all the thermodynamic properties will be loaded into the double array which contains the thermodynamic variables as: a[0], P - pressure kPa; a[1], t - temperature ^{0}C; a[2], v - specific volume m^3kg^{-1}; a[3], h - enthalpy kj kg^{-1}; a[4], u - internal energy kj kg^{-1}; a[5], s - entropy kj kg^{-1} K^{-1}; a[6], x - quality (kg vapor)(kg total phase)$^{-1}$; a[7], ρ - density kgm^{-3}. A user interface class "refTable" was also developed to use as standalone program. A demonstration of refrigerant.java interface programs were given in Figure 1 and, also output of the program code was shown in figure 1.



a-) R1234yf refrigerant in superheated vapor region at T=10 C and P=50kPa



b-) R410A refrigerant mixture in superheated vapor region at T=10 C and P=50kPa

Figure 1. A demonstration of Refrigerant.java interface programs (RefISO17584Table. java) for calculating R1234yf and R410A refrigerants thermodynamic properties as pressure(P), temperature(T), specific volume(v), enthalpy(h), internal energy(u), entropy(s), quality(x), density and phase.

The new developed program can be used for all three regions (subcooled, mix-phase, superheated and saturated lines of refrigerant fluid). The user can select the application range for any refrigerant to be obtained thermodynamic properties according the specific need of the user, at first. Then, the user can obtain the thermodynamic properties of the selected fluid with the proposed program in the specific range.

4. Modeling Results and Discussion

In this study, two mathematical approaches were used for calculating pure refrigerants thermodynamic properties. In the saturated region; saturated liquid, saturated vapor and mixed phase, Cubic spline curve fitting method (*CSCFM*) was applied to obtain more accurate results. The data source for applying Cubic spline curve fitting method in the developed program comes from actual value tables [31]. The other method, Helmholtz equation of state (*HEoS*) was applied to obtain more appropriate thermodynamic properties in the subcooled liquid and superheated regions.

R1234yf and R410A were selected as a representative refrigerant to illustrate how to use the new developed program for the determination of thermal properties in this study. Considering the usual application conditions of R1234yf, the expected application range of temperature was changed between 233 K and 448 K at superheated region, between 238 K and 410 K at subcooled region, between 230 K and 360 K at saturated region of R1234yf refrigerant. Similarly, considering the usual application conditions of R410A, the expected application range of temperature was changed between 185 K and 460 K at superheated region, between 185 K and 333 K at subcooled region, between 185 K and 345 K at saturated region of R410A refrigerant mixture. A regular increase in the saturation temperature of refrigeration was used for the fitting and accuracy evaluation process. Absolute and mean deviations were evaluated for every thermodynamic properties of R1234yf and R410A in all three regions.

The source data for regressing was obtained from REFPROP 9.0. With the new developed program, thermodynamic properties of R1234yf and R410A for all regions were predicted and compared with REFPROP 9.0 [14]. Because REFPROP 9.0 is widely used for predicting thermodynamic properties of refrigerants, which is based on the most accurate pure fluid and mixture models currently available, and the uncertainty in density, entropy and enthalpy for R1234yf and R410A is within 0,5%. Therefore, REFPROP 9.0 was used to generate data source for regression, and the accuracy was also compared with REFPROP 9.0.

In order to assess the accuracy of the proposed program, a finer temperature spacing of 10 K in superheated region for R410A, 5 K in superheated, subcooled and saturated region for R1234yf and 5 K in subcooled and saturated region for R410A was used. However, in the vicinity of the critical point, the saturated thermal properties vary dramatically, and are not known accurately or even cannot be determined by REFPROP 9.0. For these reasons, this region of the saturation curve was excluded from the analysis.

4.1. Data Ranges and Parameters of a Refrigerant Fluid

The range of the thermodynamic properties include subcooled, saturated, two-phase and superheated refrigerant with the pressure up to the critical pressure, shown as regions in Fig. 2. This figure is a sketch of the p-h diagram of every refrigerant. The trait shown in Fig. 2 prevail R1234yf and R410A refrigerants considered in this paper. The regions where the superheated, saturated, mix phases and subcooled refrigerant thermal properties were determined, were shown in Fig. 2. These regions were bounded at the bottom and top by the minimum saturation pressure (P_{min}) and the critical pressure, respectively. The minimum pressure considered was that of a saturated liquid at T_{min}= 230 K for R1234yf and T_{min}= 184,92 K for R410A refrigerant.

Super heated region was bounded at the left and right, by the saturated vapor curve and a constant superheat degree curve (ΔT_{sh}), respectively. The range of the saturated thermodynamic properties include saturated liquid and vapor thermal properties, with pressures up to the critical pressure, as shown in Fig. 2. As it can be seen, saturated line bounded as the right-hand part and the left-hand part of the dome of the saturation curve overhangs from the critical point to P_{min}. Also, two-phase region (vapor-liquid equilibrium) is a zone bounded between saturated liquid line and saturated vapor line. The subcooled fluid is defined as a region on the left-hand side of the saturated liquid line.

In this study, the region bounded from the P_A= 3000 kPa to P_B= 5 kPa for R1234yf in all phases, P_A= 1500 kPa to P_B= 10 kPa for R410A in superheated region and P_A= 4900 kPa to P_B= 10 kPa for R410A in subcooled and saturated regions on the sketch of the p-h diagram was used for calculating thermal properties . Coefficient values of R1234yf refrigerant were given in table 1 and table 2 for superheated and saturated thermal properties, as an ideal and real gas. These coefficients are valid within the following ranges: T_{min}= 200 K, T_{max}= 400 K, P_{max}= 10 MPa, ρ_{max}= 4.17 mol l^{-1} (475,55 kg m^{-3}). In order to ensure the accuracy of the new program, all the coefficients were in the format of double precision in programming and so have long digits. An equation of state for pure fluid may express the reduced molar Helmholtz energy, as a function of temperature and density. In equation of states, critical parameters and physical properties of R1234yf were used for reducing molar Helmholtz energy. Reducing Parameters, molar mass and gas constant were given as: T^*=367, 85 K, ρ^*=4, 17 mol l^{-1}, M=114,04159 g $(mol)^{-1}$, R=8, 314471 J $(mol.K)^{-1}$.

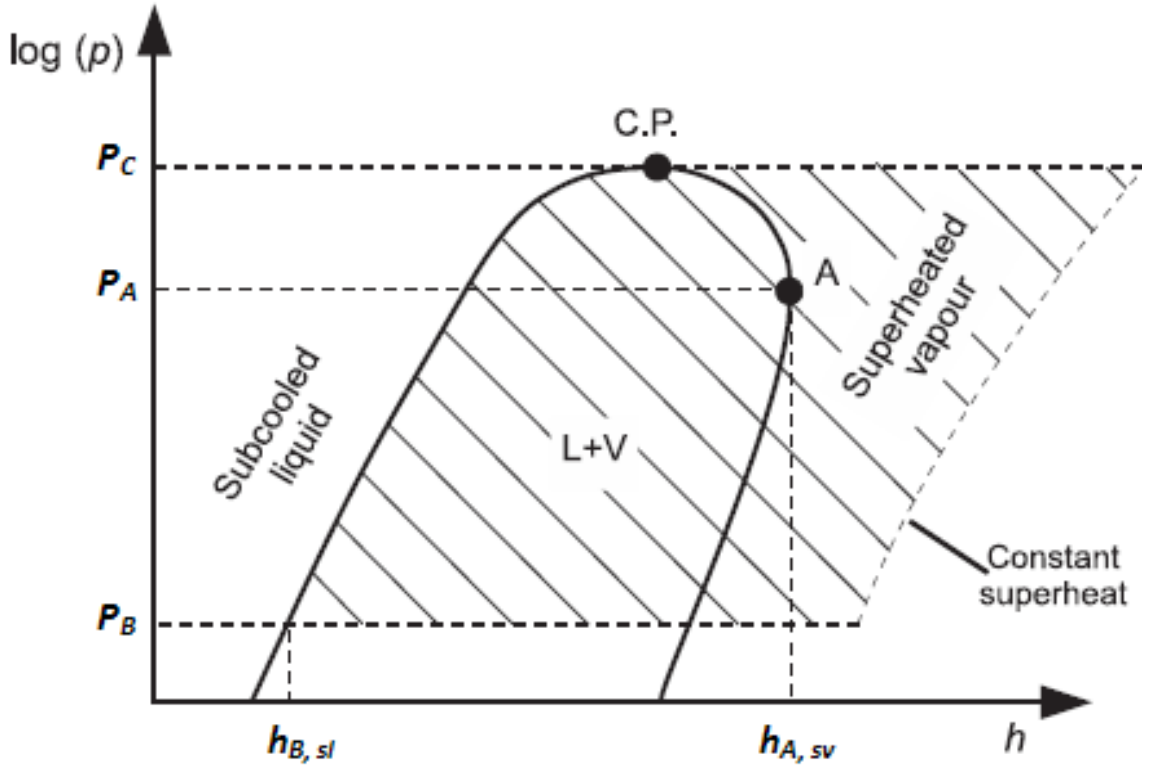


Figure 2. Range of application of subcooled, saturated and superheated refrigerant thermal properties on the pressure - enthalpy diagram: (L+V) liquid –vapor phase, (C.P.) critical point, ($h_{B, sl}$) saturated liquid enthalpy in pressure P_B, ($h_{A, sv}$) saturated vapor enthalpy in pressure P_A, (P_C) critical point pressure, (P_A and P_B) maximum and minimum operating range pressures in the proposed program

Table 1. Values for v_i and u_i in equation 2.6.a

i	v_i	u_i
1	7,549	718,0
2	1,537	877,0
3	2,030	4465,0
4	7,455	1755,0

Table 2. Coefficients and exponents of the real gas part for R1234yf refrigerant

k^a	$N_k{}^b$	$t_k{}^d$	$d_k{}^d$	$l_k{}^d$	$\alpha_k{}^c$	$\beta_k{}^c$	$\gamma_k{}^c$	$\varepsilon_k{}^c$
1	0,04592563	1,0	4	0	0	0	0	0
2	1,546958	0,32	1	0	0	0	0	0
3	-2,355237	0,929	1	0	0	0	0	0
4	-0,4827835	0,94	2	0	0	0	0	0
5	0,1758022	0,38	3	0	0	0	0	0
6	-1,210006	2,28	1	2	0	0	0	0
7	-0,6177084	1,76	3	2	0	0	0	0
8	0,685262	0,97	2	1	0	0	0	0
9	-0,6968555	2,44	2	2	0	0	0	0
10	-0,02695779	1,05	7	1	0	0	0	0
11	1,389966	1,4	1	0	1,02	1,42	1,13	0,712
12	-0,4777136	3,0	1	0	1,336	2,31	0,67	0,910
13	-0,1975184	3,5	3	0	1,055	0,89	0,46	0,677
14	-1,147646	1,0	3	0	5,84	80,0	1,28	0,718
15	0,0003428541	3,5	2	0	16,2	108,0	1,20	1,640

[a] Constant (0, 1, 2…, n) used in Eq. 2.2.a
[b] Numerical coefficients which is fitted to experimental data used in Eq. 2.2.a
[c] Certain multipliers for special refrigerant used in Eq. 2.2.a
[d] Certain upper coefficients for special refrigerant used in Eq. 2.2.a

Table 3. Composition of R410A

i	Component	Mass Fraction	Mole Fraction
1	R32	0,50	0,69761470
2	R125	0,50	0,30238530

Table 4. Coefficient and exponents of the excess functions for R410A [Equation (2.12)]

	R32/125 Binary Pair[a]			
k	N_k	t_k	d_k	l_k
1	-0,0072955	4,50	2	1
2	0,078035	0,57	5	1
3	0,61007	1,90	1	2
4	0,64246	1,20	3	2
5	0,014965	0,50	9	2
6	-0,34049	2,60	2	3
7	0,085658	11,40	3	3
8	-0,064429	4,50	6	3
[a] F_{12}=1,00, i=1; j=2.				

In order to give a quantitative principle for selecting a suitable reference state, case study at the sensitivity of temperature difference between the reference state and the critical point on the prediction effects were needed. In all thermodynamic property calculations for superheated region of R1234yf, reference state parameters and its coefficients were taken as fallow: T_{ref}=273, 15 K, P_{ref}= 1, 0 kPa, f_1=-12,837928, f_2=8, 042605. Also, the reference states, h_{ref} and s_{ref} were chosen to yield a reference state for enthalpy of 200 kJ.kg^{-1} and for entropy of 1 kJ.kg^{-1} K^{-1}, both for the saturated liquid at 0 ^{0}C.

Accordingly, Coefficient values of R410A refrigerant mixture were given in table 3 and table 4 for superheated and saturated thermal properties, as an ideal and real gas. These coefficients are valid within the following ranges: T_{min}= 172,52 K, T_{max}= 435 K, $P_{max.}$=60 MPa, ρ_{max}= 20,2 mol l^{-1} (1496 kg m^{-3}). In order to ensure the accuracy of the new program, all the coefficients were in the format of double precision in programming and so have long digits. An equation of state for refrigerant mixture may express the reduced molar Helmholtz energy, as a function of temperature and density. In equation of states, critical parameters and physical properties of R410A(based on its composition(R32 & R125)) were used for reducing molar Helmholtz energy. Reducing Parameters, molar mass and gas constant were given as: T*=344,51 K, ρ*=459, 5 kg m^{-3}, M=72,5855 g (mol)$^{-1}$, R=8, 314471 J (mol. K)$^{-1}$.

In order to give a quantitative principle for selecting a suitable reference state, case study at the sensitivity of temperature difference between the reference state and the critical point on the prediction effects were needed. In all thermodynamic property calculations for superheated region of R410A, reference state parameters and its coefficients were taken as fallow: T_{ref}=273, 15 K, P_{ref}= 1, 0 kPa, f_3=0,617469323,f_4=-0,596795,

$\zeta_{12} = 28{,}95$, $\xi_{12} = -0{,}006008$, F_{12}=1,00.

4.2. Accuracy Assessment of Developed Computer Program

Statistical analyses are used for determining the overall estimated accuracy of the model, and defining the ranges of estimated uncertainties due to the various properties calculated with the program.

The statistics used for evaluating the equation were based on the percent (absolute) deviation for any property, X,

$$\%\Delta X = [(X_{data}-X_{calc})/X_{data}].100 \quad (4.1)$$

Using this definition, the average absolute deviation (Mean deviation) was defined as

$$MD = \frac{1}{n}\sum_{i=1}^{n}(\%\Delta X) \quad (4.2)$$

Where n is the number of data points. The uncertainties of calculated values of various properties for the R1234yf and R410A refrigerant regions were predicted to have a clear demonstration of the accuracy of the proposed program, sensitivity of thermal properties by comparisons with REFPROP values. The obtained thermodynamic properties from the developed program were compared to the REFPROP data by the use of the mean and absolute deviation as given by Eq. (4.1) (4.2). Under the prediction range (for superheated region of R1234yf, temperature in 233 K and 448 K, for subcooled region, temperature in 238 K and 410 K, for saturated region, 230 K and 360 K, pressure in 0,05-3 MPa for three regions. Similarly, for superheated region of R410A, temperature in 185 K and 460 K, pressure in 0,01-1,5 MPa, for subcooled region, temperature in 184 K and 333 K, pressure in 0,01-4,9 MPa, for saturated region,

temperature in 185 K and 345 K, pressure in 0,01-4,9 MPa). we ran the developed computer program for R1234yf when the temperature data were separated into temperature increments of 5 K and for R410A when the temperature data were seperated into temperature increments of 5 K in subcooled and saturated regions, 10 K in superheated region.

The comparisons of the developed program to REFPROP data exhibit many general trends, as shown in the tables presented in this study. Summary comparisons of values calculated using the programs to data for ρ –h – s, density, specific enthalpy and specific entropy for R1234yf and R410A refrigerants were given in Tables (5,6,7,8,9,10,11,12), along with the temperature range of the data.

4.2.1. Superheated and Sub Cooled Refrigerant Thermal Properties

In most of refrigeration simulations that involve superheated refrigerant states, the temperature was usually considered as an input parameter. The thermal properties of most interest are: pressure, specific enthalpy, specific entropy, and density. When each of them are known in conjunction with the temperature, the other three can be determined. Consequently, it should be noted that when the value of the pressure and temperature are given as a fixed data, then the calculated specific enthalpy, entropy and density show all monotonic trends with temperature.

Discussions of maximum errors or of systematic offsets always use the absolute values of the deviations. Table 5(superheated), table 7(subcooled) for R410A and table 6(superheated), table 8(subcooled) for R1234yf showed the absolute deviations of the calculated properties with those from REFPROP 9.0. Also, a review of the results of Table 5 revealed that; the maximum absolute deviations for the density were almost 0,16555 % at 215 K, the maximum absolute deviations for the specific enthalpy were almost 0,038 % at 185 K, and the maximum absolute deviations for the specific entropy were almost 0,0399% at 460 K in superheated region for R410A refrigerant. Similarly, a review of the results of Table 6 revealed that; the maximum absolute deviations for the density were almost 0,4457 % at 423 K, the maximum absolute deviations for the specific enthalpy were almost 0,410 % at 448 K, and the maximum absolute deviations for the specific entropy were almost 0,3193% at 408 K in superheated region for R1234yf refrigerant. The maximum absolute deviations for the density were almost 0,08187% at 290K, the maximum absolute deviations for the specific enthalpy were almost 0,2583 % at 215K and the maximum absolute deviations for the specific entropy were almost 0,0807% at 295K in subcooled region for R410A refrigerant. Similarly, the maximum absolute deviations for the density were almost 0,4553% at 408K, the maximum absolute deviations for the specific enthalpy were almost 0,4221 % at 393K and the maximum absolute deviations for the specific entropy were almost 0, 3887% at 408K in subcooled region for R1234yf refrigerant.

The mean deviations of the calculated thermal properties of R1234yf and R410A for the superheated and subcooled regions were made comparison with REFPROP 9.0, and all the mean deviation of R1234yf and R410A thermal properties (ρ, h and s) collected in the same tables. The mean deviations (uncertainties) in the calculation of thermodynamic properties were: 0,21957% in density, 0,1906% in specific enthalpy and 0,1461% in specific entropy for R1234yf refrigerant, accordingly, 0,0232% in density, 0,0132% in specific enthalpy and 0,0203% in specific entropy for R410A refrigerant in the superheated region . It can be seen that the mean deviations of the calculated enthalpy, entropy and specific volume were acceptable and lower than 0.5%. Similar results were also found for thermal properties of R1234yf and R410A in subcooled region.

Table 5. Predicting of thermodynamic properties(Helmholtz Equation of State was utilized) and deviations for R410A refrigerant in superheated region

T(K)	P(MPa)	REFPROP 9.0Estimated Values for ρ(kgm-3)	REF ISO17584 Estimated Values for ρ(kgm-3)	Mean Deviation (%)	REFPROP 9.0 Estimated Values for h(kjkg-1)	REF ISO17584 Estimated Values for h(kjkg-1)	Mean Deviation (%)	REFPROP 9.0 Estimated Values for s(kjkg-1K-1)	REF ISO17584 Estimated Values for s(kjkg-1K-1)	Mean Deviation (%)
85	0,01	0,54353	0,54356	0,00551917	341,43	341,56	0,038060663	1,8909	1,8912	0,015862944
195	0,015	0,67917	0,67924	0,010305636	385,05	385,18	0,033750454	2,0798	2,0801	0,014422384
205	0,02	0,86194	0,86198	0,004640479	391,58	391,64	0,015320192	2,0799	2,0803	0,019227996
215	0,03	1,236	1,238	0,161550889	398,04	398,09	0,012559974	2,0649	2,0653	0,019367646
225	0,04	1,5769	1,5774	0,03169773	404,77	404,82	0,012351168	2,063	2,0634	0,01938548
235	0,05	1,8885	1,889	0,026469031	411,71	411,76	0,012142996	2,068	2,0684	0,019338619
245	0,06	2,1742	2,1745	0,013796275	418,85	418,91	0,014322886	2,0772	2,0775	0,014440433
255	0,07	2,4368	2,4372	0,016412276	426,16	426,18	0,004692853	2,0891	2,0896	0,023928025
265	0,08	2,679	2,6796	0,022391402	433,65	433,69	0,009223178	2,1028	2,103	0,009510223
273	0,09	2,9257	2,9261	0,013670073	439,7	439,73	0,006822368	2,1121	2,1124	0,014201856
275	0,1	3,2315	3,2319	0,012376621	441,07	441,12	0,011334784	2,1052	2,1056	0,01899696
285	0,12	3,745	3,7456	0,016018795	448,71	448,74	0,006685386	2,112	2,1124	0,018935808
295	0,14	4,2231	4,2234	0,007103282	456,53	456,56	0,006570878	2,1216	2,122	0,018850141
305	0,16	4,6691	4,6695	0,008566228	464,54	464,58	0,008609927	2,1333	2,1339	0,028117531
315	0,18	5,0858	5,0861	0,005898429	472,72	472,75	0,006345849	2,1465	2,1468	0,013974287
325	0,2	5,4761	5,4764	0,005478051	481,07	481,12	0,010392418	2,1607	2,161	0,013882462
335	0,25	6,6563	6,6565	0,003004582	489,23	489,28	0,010219097	2,1604	2,1608	0,018511662
345	0,3	7,7693	7,7696	0,003861203	497,61	497,65	0,008037778	2,1646	2,1648	0,009238729
355	0,35	8,8196	8,8201	0,00566887	506,19	506,24	0,009876738	2,1719	2,1724	0,023016019
365	0,4	9,8114	9,8118	0,004076724	514,97	515,01	0,007766839	2,1814	2,1818	0,018333486
375	0,45	10,749	10,7496	0,005581603	523,94	523,99	0,009542167	2,1925	2,1928	0,013681138
385	0,5	11,635	11,64	0,042955326	533,08	533,13	0,009378576	2,2048	2,2052	0,018138944
395	0,6	13,642	13,645	0,021986075	542,01	542,06	0,009224071	2,2073	2,2075	0,009060023
405	0,7	15,55	15,556	0,038570327	551,15	551,28	0,023581483	2,213	2,2136	0,027105168
415	0,8	17,366	17,372	0,034538338	560,49	560,58	0,0160548	2,221	2,2218	0,036006841
425	0,9	19,093	19,099	0,031415257	570,03	570,12	0,01578615	2,2306	2,2312	0,026891359
435	1	20,737	20,744	0,033744697	579,75	579,84	0,015521523	2,2416	2,2424	0,035676061
445	1,2	24,404	24,412	0,032770768	589,05	589,16	0,01867065	2,2425	2,2432	0,031205421
455	1,4	27,914	27,924	0,035811488	598,59	598,68	0,015033073	2,2467	2,2472	0,022249911
460	1,5	29,612	29,624	0,040507696	603,44	603,56	0,019882033	2,2497	2,2506	0,039989336

Table 6. Predicting of thermodynamic properties (Helmholtz Equation of State was utilized) and deviations for R1234yf refrigerant in superheated region

T(K)	P(MPa)	REFPROP 9.0 Estimated Values for ρ(kgm-3)	REF ISO17584 Estimated Values for ρ(kgm-3)	Mean Deviation (%)	REFPROP 9.0 Estimated Values for h(kjkg-1)	REF ISO17584 Estimated Values for h(kjkg-1)	Mean Deviation (%)	REFPROP 9.0 Estimated Values for s(kjkg-1K-1)	REF ISO17584 Estimated Values for s(kjkg-1K-1)	Mean Deviation (%)
233	0,05	3,021148036	3,02091	0,007879	337	337,17	0,05041967	1,62	1,6212	0,074019245
238	0,055	3,255208333	3,25481	0,0122368	340,7	340,91	0,061599836	1,63	1,6303	0,018401521
243	0,06	3,47947112	3,47874	0,0210124	344,5	344,72	0,063819912	1,639	1,6399	0,054881395
248	0,065	3,694126339	3,69365	0,0128945	348,4	348,6	0,057372347	1,649	1,65	0,060606061
253	0,07	3,900156006	3,89962	0,0137432	352,3	352,54	0,068077381	1,66	1,6605	0,030111412
258	0,075	4,096681688	4,09613	0,0134667	356,3	356,54	0,067313625	1,67	1,6712	0,071804691
263	0,08	4,286326618	4,28526	0,0248842	360,3	360,6	0,083194676	1,681	1,6822	0,071335156
268	0,09	4,739336493	4,73899	0,007311	364,3	364,62	0,087762602	1,688	1,6889	0,053289123
273	0,1	5,175983437	5,17498	0,0193864	368,4	368,7	0,081366965	1,695	1,6966	0,09430626
278	0,101325	5,141388175	5,14045	0,0182475	372,7	373	0,080428954	1,71	1,7112	0,070126227
283	0,11	5,488474204	5,48742	0,0192076	376,9	377,23	0,087479787	1,719	1,7204	0,081376424
288	0,12	5,885815185	5,88488	0,0158888	381,1	381,49	0,102230727	1,728	1,7292	0,069396253
293	0,13	6,273525721	6,26996	0,0568376	385,4	385,81	0,106269926	1,737	1,7383	0,07478571
298	0,14	6,644518272	6,63566	0,133317	389,8	390,19	0,099951306	1,747	1,7479	0,05149036
303	0,15	7,00280112	6,99196	0,1548112	394,2	394,62	0,106431504	1,756	1,7577	0,096717301
308	0,16	7,352941176	7,33696	0,217344	398,7	399,11	0,102728571	1,766	1,7678	0,101821473
313	0,17	7,686395081	7,66964	0,2179836	403,2	403,65	0,11148272	1,777	1,7782	0,067483973
318	0,18	8,012820513	7,99674	0,2006848	407,8	408,24	0,107779737	1,787	1,7886	0,08945544
323	0,19	8,326394671	8,30864	0,2132336	412,4	412,88	0,116256539	1,798	1,7993	0,07225032
328	0,2	8,628127696	8,60875	0,2245875	417,1	417,57	0,112555979	1,809	1,81	0,055248619
333	0,22	9,36329588	9,34377	0,2085364	421,7	422,21	0,12079297	1,816	1,8173	0,071534694

338	0,24	10,08064516	10,06261	0,1789088	426,3	426,9	0,140548138	1,824	1,8251	0,06027067
343	0,26	10,77586207	10,753111	0,21112992	431,1	431,65	0,127418047	1,832	1,8334	0,07636086
348	0,28	11,4416476	11,418008	0,20661008	435,8	436,44	0,146641004	1,84	1,842	0,108577633
353	0,3	12,09189843	12,06096	0,2558608	440,6	441,29	0,156359763	1,849	1,851	0,108049703
358	0,35	13,98601399	13,95056	0,253496	445,2	445,93	0,163702823	1,851	1,8532	0,118713577
363	0,4	15,82278481	15,78118	0,2629424	449,8	450,64	0,186401562	1,855	1,8569	0,102321073
368	0,45	17,6056338	17,55132	0,3085024	454,5	455,41	0,199819942	1,859	1,8617	0,145028737
373	0,5	19,37984496	19,32462	0,2849608	459,2	460,23	0,223801143	1,865	1,8674	0,128520938
378	0,6	23,14814815	23,08035	0,292888	463,5	464,73	0,264669808	1,864	1,8668	0,149989286
383	0,7	26,80965147	26,72637	0,3106399	467,9	469,31	0,300441073	1,865	1,8682	0,171287871
388	0,8	30,48780488	30,38783	0,3279176	472,4	473,95	0,327038717	1,867	1,8711	0,219122441
393	0,9	34,01360544	33,88708	0,3719848	477	478,66	0,346801487	1,871	1,8752	0,223976109
398	1	37,59398496	37,45318352	0,374531835	481,6	483,18	0,32700029	1,876	1,881	0,265816055
403	1,2	45,04504505	44,86316734	0,403768506	485,4	487,18	0,365368036	1,873	1,878	0,266240682
408	1,4	52,63157895	52,41090147	0,419287212	489,3	490,65	0,275145216	1,873	1,879	0,319318787
413	1,6	60,24096386	60,0240096	0,360144058	493,4	494,81	0,284957863	1,874	1,88	0,319148936
418	1,8	67,56756757	67,29475101	0,403768506	497,5	498,96	0,292608626	1,876	1,882	0,318809777
423	2	74,62686567	74,29420505	0,44576523	501,7	503,72	0,401016438	1,879	1,885	0,318302387
428	2,2	81,96721311	81,63265306	0,408163265	506,1	508,12	0,397543887	1,884	1,89	0,317460317
433	2,4	89,28571429	88,88888889	0,444444444	510,5	512,56	0,401904167	1,889	1,895	0,316622691
438	2,6	96,15384615	95,6937799	0,4784689	515	516,96	0,379139585	1,894	1,9	0,315789474
443	2,8	103,0927835	102,6694045	0,410677618	519,7	521,76	0,394817541	1,9	1,906	0,314795383
448	3	108,6956522	108,2251082	0,432900433	524,4	526,56	0,410209663	1,906	1,912	0,313807531

Table 7. Predicting of thermodynamic properties (Helmholtz Equation of State was utilized) and deviations for R410A refrigerant in subcooled region

T(K)	P(MPa)	REFPROP 9.0 Estimated Values for ρ(kgm-3)	REF ISO17584 Estimated Values for ρ(kgm-3)	Mean Deviation (%)	REFPROP 9.0 Estimated Values for h(kjkg-1)	REF ISO17584 Estimated Values for h(kjkg-1)	Mean Deviation (%)	REFPROP 9.0 Estimated Values for s(kjkg-1K-1)	REF ISO17584 Estimated Values for s(kjkg-1K-1)	Mean Deviation (%)
185	0,01	1463,3	1463,8	0,034157672	75,321	75,4	0,104774536	0,45212	0,45218	0,013269052
190	0,015	1445,8	1446,4	0,041482301	83,388	83,48	0,110206037	0,49525	0,49536	0,022206072
195	0,02	1434	1434,5	0,03485535	88,769	88,96	0,214703237	0,52326	0,52334	0,015286429
200	0,03	1416,2	1416,8	0,042348955	96,853	96,88	0,027869529	0,56426	0,56434	0,014175851
205	0,04	1404,2	1404,6	0,028477858	102,25	102,45	0,195217179	0,59096	0,59102	0,010151941
210	0,06	1386	1386,8	0,057686761	110,38	110,6	0,198915009	0,63016	0,63024	0,012693577
215	0,08	1373,7	1374,2	0,036384806	115,82	116,12	0,258353427	0,65574	0,65584	0,015247621
220	0,1	1355,1	1355,6	0,036884037	124,01	124,24	0,185125563	0,69341	0,69345	0,00576826
225	0,12	1342,5	1343,2	0,052114354	129,5	129,8	0,231124807	0,71806	0,71814	0,011139889
230	0,16	1323,3	1324,2	0,067965564	137,78	138,02	0,173887842	0,75441	0,75448	0,009277913
235	0,2	1310,3	1310,9	0,045770082	143,33	143,48	0,104544187	0,77824	0,77832	0,010278549
240	0,25	1290,4	1291	0,0464756	151,73	152,01	0,184198408	0,8135	0,81356	0,007374994
245	0,3	1277	1277,5	0,039138943	157,37	157,48	0,06985014	0,83667	0,83672	0,005975715
250	0,4	1256,4	1256,8	0,031826862	165,92	166,22	0,180483696	0,87096	0,87104	0,009184423
255	0,5	1242,4	1243	0,048270314	171,68	172,02	0,197651436	0,8935	0,89354	0,004476576
260	0,6	1220,7	1221,3	0,049127978	180,41	180,56	0,083074878	0,92712	0,92718	0,006471235
265	0,7	1206	1206,8	0,066291018	186,29	186,54	0,134019513	0,94928	0,94934	0,00632018
270	0,8	1182,8	1183,4	0,050701369	195,24	195,64	0,204457166	0,98248	0,98254	0,006106622
273	0,9	1171,1	1171,6	0,042676681	199,78	200,02	0,119988001	0,99887	0,99894	0,007007428
280	1	1141,9	1142,5	0,052516411	210,53	210,84	0,147030924	1,0375	1,038	0,048169557
285	1,2	1125,3	1125,9	0,053290701	216,79	216,99	0,092170146	1,059	1,0596	0,056625142
290	1,4	1098,4	1099,3	0,081870281	226,38	226,56	0,079449153	1,0918	1,0924	0,054924936
295	1,6	1080,1	1080,8	0,064766839	232,9	233,24	0,145772595	1,1135	1,1144	0,080760948
300	1,8	1049,9	1050,6	0,066628593	242,96	243,12	0,065811122	1,1468	1,1476	0,069710701
305	2	1029	1029,8	0,077684987	249,83	250,06	0,091977925	1,1689	1,1694	0,042756969
310	2,5	998,17	998,24	0,007012342	260,28	260,54	0,099792738	1,2013	1,202	0,058236273
315	3	979,05	979,3	0,025528439	267,22	267,34	0,044886661	1,2219	1,2226	0,05725503
320	3,5	944,44	944,64	0,021172087	278,24	278,36	0,043109642	1,255	1,2558	0,063704412
325	4	923,41	923,91	0,054117825	285,5	285,64	0,049012743	1,2759	1,2765	0,047003525
330	4,5	883,44	883,74	0,033946636	297,31	297,52	0,07058349	1,3103	1,3112	0,068639414
333	4,9	866,71	866,94	0,026530094	302,97	303,12	0,049485352	1,326	1,3265	0,037693178

Table 8. Predicting of thermodynamic properties(Helmholtz Equation of State was utilized) and deviations for R1234yf refrigerant in subcooled region

T(K)	P(MPa)	REFPROP 9.0 Estimated Values for ρ(kgm-3)	REF ISO17584 Estimated Values for ρ(kgm-3)	Mean Deviation (%)	REFPROP 9.0 Estimated Values for h(kjkg-1)	REF ISO17584 Estimated Values for h(kjkg-1)	Mean Deviation (%)	REFPROP 9.0 Estimated Values for s(kjkg-1K-1)	REF ISO17584 Estimated Values for s(kjkg-1K-1)	Mean Deviation (%)
238	0,05	2,9535	2,9538	0,010156409	177,34	177,41	0,039456626	0,7774	0,7775	0,012861736
243	0,055	3,1836	3,184	0,012562814	181,13	181,24	0,060693004	0,78636	0,78646	0,012715205
248	0,06	3,4042	3,4044	0,00587475	184,98	185,16	0,097213221	0,79586	0,79594	0,010051009
253	0,065	3,6158	3,6161	0,008296231	188,89	189,03	0,074062318	0,8058	0,806	0,024813896
258	0,07	3,8188	3,8192	0,010473398	192,87	193,02	0,077712154	0,8161	0,8164	0,036746693
263	0,075	4,0138	4,0141	0,007473655	196,91	197,08	0,086259387	0,82669	0,8271	0,04957079
268	0,08	4,2012	4,2016	0,009520183	201	201,24	0,119260584	0,83754	0,83772	0,021486893
273	0,09	4,6465	4,647	0,01075963	205,05	205,29	0,116907789	0,84413	0,84445	0,037894488
278	0,1	5,0759	5,0764	0,0098495	209,16	209,37	0,100300903	0,85158	0,85216	0,068062336
283	0,12	6,0061	6,0065	0,006659452	213,14	213,36	0,103112111	0,85287	0,85324	0,043364118
288	0,14	6,9081	6,9086	0,007237356	217,2	217,46	0,119562218	0,85622	0,85674	0,060695193
293	0,16	7,7823	7,7829	0,007709209	221,33	221,65	0,144371757	0,86107	0,86184	0,08934373
298	0,18	8,6293	8,6298	0,005793877	225,54	225,88	0,150522401	0,86705	0,86745	0,046112168
303	0,2	9,4497	9,4501	0,004232759	229,81	230,21	0,173754398	0,87392	0,87454	0,070894413
308	0,22	10,244	10,249	0,048785247	234,16	234,56	0,17053206	0,88148	0,88196	0,054424237
313	0,24	11,013	11,017	0,036307525	238,57	238,97	0,167385027	0,88962	0,89016	0,060663252
318	0,26	11,758	11,763	0,042506163	243,04	243,48	0,180712995	0,89822	0,89896	0,082317344
323	0,28	12,479	12,485	0,048057669	247,57	248,04	0,189485567	0,90721	0,90841	0,132098942
328	0,3	13,178	13,186	0,060670408	252,16	252,64	0,189993667	0,91652	0,91756	0,113344086
333	0,35	15,229	15,234	0,032821321	256,41	256,96	0,214041096	0,9187	0,92016	0,158668058
338	0,4	17,234	17,241	0,040600893	260,73	261,24	0,195222784	0,92241	0,92364	0,133168767
343	0,45	19,191	19,199	0,041668837	265,14	265,69	0,207008167	0,92727	0,92906	0,192667858
348	0,5	21,1	21,131	0,146703895	269,62	270,25	0,233117484	0,93305	0,93452	0,157300004
353	0,6	25,229	25,265	0,14248961	273,57	274,32	0,273403325	0,93197	0,93344	0,157482002
358	0,7	29,304	29,342	0,129507191	277,62	278,52	0,323136579	0,93302	0,93454	0,162646864
363	0,8	33,319	33,389	0,209649885	281,76	282,72	0,339558574	0,93565	0,93765	0,213299205
368	0,9	37,266	37,374	0,288970942	286	286,96	0,334541399	0,93948	0,94148	0,212431491
373	1	41,138	41,288	0,363301686	290,33	291,24	0,31245708	0,94428	0,94628	0,211353933
378	1,2	49,628	49,814	0,373389007	293,64	294,64	0,339397231	0,94131	0,94348	0,229999576
383	1,4	58,132	58,375	0,41627409	297,06	297,96	0,302053967	0,94053	0,94319	0,28202165
388	1,6	66,617	66,848	0,345560077	300,61	301,84	0,407500663	0,9414	0,94434	0,311328547
393	1,8	75,044	75,296	0,334679133	304,27	305,56	0,422175677	0,94355	0,94625	0,285336856
398	2	83,38	83,694	0,375176237	308,07	309,34	0,410551497	0,94675	0,94996	0,337908965
403	2,2	91,587	91,899	0,33950315	311,99	313,19	0,383153996	0,95083	0,95415	0,347953676
408	2,5	104,93	105,41	0,455364766	314,97	316,26	0,407892241	0,95065	0,95436	0,388742194
410	3	131,87	132,2	0,249621785	312,01	313,24	0,392670157	0,93301	0,93664	0,387555518

4.3. Two-phase and Saturated Refrigerant Thermal Properties

For a pure refrigerant (saturated liquid and vapor) or a zeotropic mixture, two-phase thermal properties can be easily obtained from the vapor quality and liquid-vapor saturation thermal properties. Therefore, this section was only focused in the determination of two-phase refrigerant thermal properties of zeotropic mixtures. The original definition of the thermodynamic vapor quality was given by the following relation:

$$x = \frac{m_v}{m_v + m_l} \tag{4.3}$$

This definition was that used in a thermodynamic diagram. Where x is the vapor quality, m_v and m_l are the vapor and the liquid mass, respectively. The two-phase enthalpy was given by the following relations:

$$h_{tp} = x.h_v + (1-x).h_l \tag{4.4}$$

Where h_{tp} is the two-phase enthalpy, h_v and h_l are the saturated vapor and the liquid enthalpies, respectively. The other properties ρ_{tp} and s_{tp} are found for using Eq. (4.4) in the same way.

In most of refrigeration simulations that involve two-phase refrigerant states, the temperature is usually considered as an input parameter. For saturated refrigerant thermal properties, a data set [28] with fine regular temperature spacing was used for the fitting process in this program. For predicting two-phase refrigerant thermal properties, a regular vapor saturation temperature increment of 5K was used for the fitting and accuracy evaluation process, excluding saturation temperatures near the critical point. The temperature spacing varied between 230K and 360K for R1234yf and 210K and 340K for R410A depending on the section and refrigerant considered. All saturated refrigerant thermal properties were obtained from (Refrigerant) using the bubble point temperature (saturated temperature) and vapor quality as an input parameter. Bubble or dew point properties are included as v –h – s data, with the bubble or dew point pressure calculated from the developed program.

Table 9, table 11 showed the results for R410A and table 10, table 12 showed the results for R1234yf at different temperatures in the saturated liquid and vapor regions. The absolute deviations of the calculated saturated thermal properties for R1234yf and R410A were obtained to be made comparison with REFPROP 9.0, and the all absolute deviations of R1234yf and R410A thermal properties (ρ , h and s) were given separately in the tables. The mean deviations in the calculation of thermodynamic properties were: for saturated liquid 0,01257% and for saturated vapor 0,0263% for R410A, similarly, for saturated liquid 0,0194% and for saturated vapor 0,0183% for R1234yf in density, for saturated liquid 0,0354% and for saturated vapor 0,02395% for R410A, similarly, for saturated liquid 0,047% and for saturated vapor 0,02985% for R1234yf in specific enthalpy and for saturated liquid 0,0366% and for saturated vapor 0,0165% for R410A,similarly, for saturated liquid 0,032% and for saturated vapor 0,012% for R1234yf in specific entropy in the saturated region.

Table 9. Predicting of thermodynamic properties(Cubic Spline Curve Fitting Method was utilized) and deviations for R410A refrigerant in saturated liquid region

T(K)	P(MPa)	REFPROP 9.0 Estimated Values for ρ(kgm-3)	REF ISO17584 Estimated Values for ρ(kgm-3)	Mean Deviation (%)	REFPROP 9.0 Estimated Values for h(kjkg-1)	REF ISO17584 Estimated Values for h(kjkg-1)	Mean Deviation (%)	REFPROP 9.0 Estimated Values for s(kjkg-1K-1)	REF ISO17584 Estimated Values for s(kjkg-1K-1)	Mean Deviation (%)
210	0,053727	1385,9	1385,909	0,000649393	110,51	110,379	0,118541308	0,63072	0,63069	0,004756469
215	0,071143	1370,5	1370,61	0,008025624	117,31	117,174	0,115932146	0,66264	0,66213	0,076964868
220	0,092819	1354,9	1355	0,007380074	124,13	124,022	0,087005559	0,69394	0,69344	0,072052339
225	0,11946	1339,2	1339,28	0,005973359	130,99	130,865	0,095427132	0,72466	0,72415	0,070377832
230	0,15182	1323,1	1323,26	0,01209135	137,88	137,77	0,079779518	0,75485	0,7544	0,059614493
235	0,1907	1306,9	1306,96	0,004590806	144,82	144,72	0,069051236	0,78456	0,78416	0,050983991
240	0,23697	1290,3	1290,4	0,007749535	151,81	151,728	0,054014887	0,81384	0,81355	0,03563354
245	0,29152	1273,4	1273,53	0,010207847	158,85	158,788	0,039030532	0,84272	0,84255	0,020172774
250	0,35531	1256,1	1256,2	0,007960516	165,96	165,91	0,030127742	0,87126	0,8686	0,305304961
255	0,42933	1238,4	1238,48	0,006459531	173,15	173,11	0,023101357	0,89948	0,8993	0,020011562
260	0,51461	1220,3	1220,33	0,002458351	180,42	180,39	0,016627868	0,92744	0,9273	0,015095316
265	0,61223	1201,6	1201,656	0,004660236	187,78	187,76	0,010650762	0,95517	0,95506	0,011516275
270	0,7233	1182,4	1182,43	0,002537148	195,24	195,245	0,002560885	0,98272	0,9827	0,002035168
275	0,84899	1162,5	1162,56	0,005161024	202,82	202,818	0,000986096	1,0101	1,01	0,00990001
280	0,99048	1141,9	1141,85	0,004378667	210,52	210,518	0,000950029	1,0375	1,0374	0,009638554
285	1,149	1120,4	1120,29	0,009817922	218,37	218,39	0,009157928	1,0647	1,06486	0,015025449
290	1,326	1098	1097,79	0,019125683	226,38	226,39	0,004417156	1,092	1,0921	0,009156671
295	1,5226	1074,4	1074,22	0,016753537	234,57	234,59	0,008525513	1,1194	1,1195	0,008932559
300	1,7404	1049,5	1049,24	0,024773702	242,97	242,99	0,008230791	1,147	1,1468	0,017436792
305	1,9809	1023,1	1022,73	0,036164598	251,61	251,64	0,011921793	1,1748	1,1746	0,017024174
310	2,2456	994,74	994,35	0,039206225	260,53	260,55	0,00767607	1,2029	1,2027	0,016626486
315	2,5364	964,04	963,7	0,035268246	269,8	269,77	0,011119348	1,2316	1,2315	0,008119519
320	2,855	930,28	930,015	0,028486047	279,49	279,47	0,007155891	1,2611	1,261	0,007929585
325	3,2037	892,34	892,276	0,007172154	289,76	289,704	0,019326339	1,2917	1,2915	0,015483471
330	3,5848	848,18	848,224	0,005187309	300,85	300,796	0,017949144	1,3243	1,324	0,022653477
335	4,0009	793,36	793,499	0,01751735	313,31	313,24	0,022342089	1,3602	1,3599	0,02205558
340	4,4556	714,34	714,41	0,009798295	328,81	329,095	0,086601133	1,4043	1,4052	0,064047822

Table 10. Predicting of thermodynamic properties (Cubic Spline Curve Fitting Method was utilized) and deviations for R1234yf refrigerant in saturated liquid region

T(K)	P(MPa)	REFPROP 9.0 Estimated Values for ρ(kgm-3)	REF ISO17584 Estimated Values for ρ(kgm-3)	Mean Deviation (%)	REFPROP 9.0 Estimated Values for h(kjkg-1)	REF ISO17584 Estimated Values for h(kjkg-1)	Mean Deviation (%)	REFPROP 9.0 Estimated Values for s(kjkg-1K-1)	REF ISO17584 Estimated Values for s(kjkg-1K-1)	Mean Deviation (%)
230	0,053393	1300,3	1300,2	0,007690533	-15,99	-16,01	0,124921924	-0,067365	-0,06736	0,007422803
235	0,068172	1286,9	1286,7	0,015541223	-10,206	-10,199	0,06863418	-0,042538	-0,0425	0,089411765
240	0,086032	1273,2	1272,9	0,023562677	-4,3456	-4,3452	0,00920556	-0,01792	-0,01791	0,055834729
245	0,1074	1259,4	1259	0,031761156	1,5937	1,593	0,043942247	0,006503	0,00649	0,199907735
250	0,13272	1245,3	1245	0,024090581	7,6131	7,6128	0,003940731	0,030742	0,03074	0,006505758
255	0,16248	1231	1230,6	0,032493907	13,714	13,709	0,03647239	0,05481	0,05479	0,036489692
260	0,19717	1216,3	1216,1	0,016443312	19,899	19,896	0,015078408	0,078718	0,078714	0,00508143
265	0,2373	1201,4	1201	0,03329449	26,168	26,164	0,015288182	0,10248	0,10244	0,039032006
270	0,28343	1186,1	1185,9	0,016861985	32,525	32,52	0,015375154	0,1261	0,12596	0,111022998
275	0,33611	1170,5	1170,2	0,025630073	38,972	38,97	0,005132153	0,14959	0,14956	0,020054816
280	0,39592	1154,4	1154,1	0,025987526	45,511	45,508	0,006592248	0,17297	0,17294	0,017344048
285	0,46346	1137,9	1137,7	0,017576237	52,145	52,143	0,003835606	0,19624	0,19622	0,010191602
290	0,53934	1120,9	1120,6	0,026764207	58,879	58,876	0,005095455	0,21943	0,2194	0,013671786
295	0,62421	1103,3	1103	0,027191154	65,714	65,71	0,006087354	0,24254	0,24251	0,012369094
300	0,71872	1085,1	1084,8	0,027647221	72,658	72,656	0,002752698	0,26559	0,26556	0,011295606
305	0,82355	1066,2	1066	0,018758207	79,714	79,71	0,005018191	0,28859	0,28856	0,010395371
310	0,93941	1046,6	1046,3	0,028664246	86,891	86,888	0,003452721	0,31158	0,31155	0,009628346
315	1,067	1026,1	1025,8	0,029236916	94,198	94,194	0,004246555	0,33456	0,33452	0,011956002
320	1,2072	1004,6	1004,2	0,039816843	101,65	101,6	0,049212598	0,3576	0,3572	0,111856823
325	1,3607	981,81	981,78	0,003055581	109,27	109,23	0,036619976	0,38074	0,3807	0,010505857
330	1,5285	957,56	957,5	0,006265926	117,07	117	0,05982906	0,40404	0,404	0,00990001
335	1,7114	931,42	931,36	0,006441777	125,1	124,8	0,240384615	0,42761	0,42756	0,011692898
340	1,9104	902,83	902,72	0,012183911	133,4	133	0,30075188	0,45156	0,4515	0,013287271
345	2,1266	871,03	870,96	0,008036463	142,04	142	0,028169014	0,47606	0,476	0,012603453
350	2,3614	834,85	834,8	0,0059891	151,11	151,02	0,059594756	0,50136	0,50131	0,009972874
355	2,6162	792,31	792,26	0,006310661	160,8	160,72	0,049776008	0,52796	0,5279	0,011364497
360	2,8931	738,91	738,86	0,006766724	171,53	171,41	0,070007584	0,55698	0,55695	0,00538619

Table 11. Predicting of thermodynamic properties (cubic spline curve fitting method was utilized) and deviations for R410A refrigerant in saturated vapor region

T(K)	P(MPa)	REFPROP 9.0 Estimated Values for ρ(kgm-3)	REF ISO17584 Estimated Values for ρ(kgm-3)	Mean Deviation (%)	REFPROP 9.0 Estimated Values for h(kjkg-1)	REF ISO17584 Estimated Values for h(kjkg-1)	Mean Deviation (%)	REFPROP 9.0 Estimated Values for s(kjkg-1K-1)	REF ISO17584 Estimated Values for s(kjkg-1K-1)	Mean Deviation (%)
210	0,053489	2,2913	2,2921	0,034902491	393,05	392,998	0,013229869	1,9763	1,976	0,015179882
215	0,070844	2,9824	2,984	0,053619303	395,76	395,72	0,010107136	1,9579	1,9578	0,005107513
220	0,092447	3,8298	3,832	0,057411273	398,41	398,357	0,013302879	1,9408	1,9406	0,010305029
225	0,119	4,8578	4,859	0,02469644	401	400,96	0,009975062	1,9249	1,9248	0,005195075
230	0,15125	6,0926	6,094	0,022973416	403,53	403,49	0,009912522	1,91	1,9099	0,005235602
235	0,19	7,5632	7,5656	0,031722534	405,98	405,946	0,008374797	1,896	1,89594	0,003164557
240	0,23611	9,3012	9,3018	0,006450364	408,35	408,308	0,010285294	1,8829	1,8828	0,005310957
245	0,29049	11,341	11,348	0,061684878	410,63	410,584	0,011202299	1,8705	1,8704	0,005346164
250	0,35407	13,722	13,7268	0,034968092	412,82	412,767	0,012838525	1,8588	1,85868	0,006455778
255	0,42786	16,487	16,49	0,018192844	414,9	414,839	0,014702338	1,8476	1,84749	0,00595367
260	0,51287	19,683	19,688	0,02539618	416,87	416,799	0,017031689	1,8369	1,8367	0,010887909
265	0,61019	23,365	23,369	0,017116693	418,7	418,633	0,016001911	1,8267	1,8265	0,010948705
270	0,72092	27,596	27,602	0,021737555	420,4	420,32	0,019029496	1,8167	1,8165	0,011008972
275	0,84622	32,447	32,45	0,009244992	421,94	421,84	0,023700052	1,807	1,8067	0,016602103
280	0,98729	38,003	38,012	0,023676734	423,3	423,2	0,023623907	1,7974	1,797	0,022254367
285	1,1454	44,367	44,372	0,011268367	424,45	424,36	0,021203911	1,7879	1,7876	0,016779462
290	1,3218	51,659	51,664	0,009677919	425,38	425,28	0,023508392	1,7783	1,778	0,016870044
295	1,5179	60,033	60,043	0,016654731	426,05	425,93	0,028165708	1,7686	1,7682	0,022616759
300	1,7351	69,68	69,702	0,031562939	426,41	426,27	0,032832251	1,7585	1,758	0,028433324
305	1,9749	80,849	80,852	0,003710483	426,41	426,26	0,035177411	1,748	1,7474	0,034324943
310	2,239	93,875	93,879	0,004260804	425,98	425,804	0,041316494	1,7367	1,7362	0,028790234
315	2,5291	109,22	109,25	0,027459954	425,02	424,827	0,045409628	1,7245	1,72387	0,036532328
320	2,8472	127,58	127,61	0,023509129	423,39	423,186	0,048182527	1,7108	1,7102	0,035071312
325	3,1955	150,02	150,12	0,066613376	420,86	420,657	0,048234567	1,6952	1,6946	0,035394054
330	3,5766	178,43	178,48	0,028014343	417,06	416,877	0,043878579	1,6765	1,6759	0,035788846
335	3,9935	216,65	216,69	0,018459551	411,22	411,073	0,035747289	1,6525	1,6523	0,012102874
340	4,4504	275,64	275,71	0,025388996	401,22	401,1	0,029908778	1,6173	1,6172	0,006183145

Table 12. Predicting of thermodynamic properties(Cubic Spline Curve Fitting Method was utilized) and deviations for R1234yf refrigerant in saturated vapor region

T(K)	P(MPa)	REFPROP 9.0 Estimated Values for ρ(kgm-3)	REF ISO17584 Estimated Values for ρ(kgm-3)	Mean Deviation (%)	REFPROP 9.0 Estimated Values for h(kjkg-1)	REF ISO17584 Estimated Values for h(kjkg-1)	Mean Deviation (%)	REFPROP 9.0 Estimated Values for s(kjkg-1K-1)	REF ISO17584 Estimated Values for s(kjkg-1K-1)	Mean Deviation (%)
230	0,053393	3,2814	3,281	0,012189919	171,03	171	0,017540782	0,74577	0,74576	0,001340896
235	0,068172	4,1242	4,122	0,053343679	174,4	174,2	0,114678899	0,74303	0,743	0,004037522
240	0,086032	5,1292	5,1288	0,007798487	177,77	177,72	0,028126231	0,74091	0,74088	0,004049075
245	0,1074	6,3179	6,3174	0,007914022	181,15	181,06	0,049682583	0,73937	0,73934	0,004057508
250	0,13272	7,7131	7,7124	0,009075469	184,51	184,48	0,016259281	0,73834	0,73832	0,002708779
255	0,16248	9,3398	9,3394	0,004282747	187,87	187,82	0,026614148	0,73776	0,73772	0,005421817
260	0,19717	11,225	11,222	0,026726058	191,2	191,06	0,073221757	0,73759	0,73756	0,0040673
265	0,2373	13,399	13,394	0,037316218	194,52	194,48	0,020563438	0,73777	0,73774	0,004066308
270	0,28343	15,894	15,89	0,02516673	197,81	197,79	0,010110712	0,73827	0,73824	0,004063554
275	0,33611	18,746	18,742	0,021337885	201,07	201,04	0,014920177	0,73903	0,739	0,004059375
280	0,39592	21,996	21,994	0,009092562	204,28	204,26	0,009790484	0,74001	0,73999	0,002702666
285	0,46346	25,688	25,686	0,007785737	207,44	207,41	0,014462013	0,74115	0,74112	0,004047764
290	0,53934	29,877	29,875	0,006694113	210,55	210,51	0,018997863	0,74243	0,74241	0,002693857
295	0,62421	34,62	34,614	0,017331023	213,58	213,55	0,014046259	0,74377	0,74374	0,004033505
300	0,71872	39,989	39,987	0,005001375	216,52	216,5	0,009237022	0,74514	0,7451	0,005368119
305	0,82355	46,066	46,062	0,008683194	219,37	219,34	0,013675525	0,74647	0,74645	0,002679277
310	0,93941	52,949	52,945	0,007554439	222,1	221,94	0,072039622	0,74772	0,74669	0,1377521
315	1,067	60,76	60,754	0,009874918	224,69	224,684	0,002670346	0,74882	0,7488	0,002670869
320	1,2072	69,648	69,645	0,004307374	227,12	227	0,052835505	0,74969	0,74964	0,006669423
325	1,3607	79,803	79,799	0,005012343	229,36	229,33	0,013079874	0,75026	0,75021	0,006664356
330	1,5285	91,475	91,471	0,004372779	231,38	231,34	0,017287579	0,75042	0,75039	0,003997761
335	1,7114	105	104,96	0,038095238	233,11	233	0,047188023	0,75003	0,75	0,00399984
340	1,9104	120,85	120,83	0,016549441	234,5	234,41	0,038379531	0,7489	0,7484	0,066764588
345	2,1266	139,73	139,68	0,035783296	235,43	235,4	0,012742641	0,74675	0,7467	0,006695681
350	2,3614	162,79	162,74	0,030714417	235,73	235,68	0,021210707	0,74315	0,74306	0,01211061
355	2,6162	192,12	192	0,062460962	235,11	234,99	0,051039939	0,7373	0,73722	0,0108504
360	2,8931	232,37	232,32	0,021517408	232,91	232,85	0,025761024	0,72746	0,72741	0,00687323

Table 13. Mean deviations of R1234yf thermal properties for the regions of a refrigerant fluid

Parameters	Mean deviations (%)			
	Subcooled	Saturated		Superheated
		Liquid	Vapor	
Density (kg.m^{-3})	0,1288	0,0194	0,0183	0,21957
Specific enthalpy (kJ. kg^{-1})	0,2183	0,047	0,032	0,1906
Specific entropy (kJ. kg^{-1}.K^{-1})	0,1443	0,032	0,012	0,1461

Table 14. Mean deviations of R410A thermal properties for the regions of a refrigerant fluid

Parameters	Mean deviations (%)			
	Subcooled	Saturated		Superheated
		Liquid	Vapor	
Density (kg.m^{-3})	0,045	0,01257	0,0263	0,0232
Specific enthalpy (kJ. kg^{-1})	0,1276	0,0354	0,02395	0,0132
Specific entropy (kJ. kg^{-1}.K^{-1})	0,0283	0,0366	0,0165	0,0203

In addition, the accurate effects of the developed computer program were shown in Table 13 and table 14 as mean deviations in the calculated thermal properties of R1234yf and R410A respectively.

5. Conclusions

A new developed program (Refrigerant) for the calculation of thermodynamic properties of pure refrigerants and refrigerant mixtures were presented in this study. The program was modeled with two different approaches: Helmholtz equation of state (*HEoS*) and cubic spline curve fitting method (*CSCFM*). Separate equations of these approaches were used for modeling different regions and properties. One of these methods (*HEoS*) was used to calculate in subcooled liquid and superheated vapor phases, and the other (*CSCFM*) to calculate saturated and mixed phases. For the superheated and subcooled states, the pressure, specific enthalpy, specific entropy and specific volume can be determined when the temperature and one of the other thermal properties were known. Also for two-phase refrigerant state, the pressure, specific enthalpy, specific entropy and specific volume can be determined when the temperature was also given as an input parameter with the vapor quality.

As an example refrigerant, R1234yf and R410A were used in the study. The source data for regressing was obtained from REFPROP 9.0. With the new model, thermodynamic properties of R1234yf and R410A were predicted and compared with REFPROP 9.0[14]. It was cleared that the total mean relative deviations of the new model were less than 0.5%. Table 13 and table 14 probed that the agreement between the calculated properties with those from REFPROP 9.0 was satisfactory. It was shown that the absolute deviations of the calculated thermal properties were always very low and within the uncertainties of the source data used for comparison and accuracy evaluation. For these reasons, this region of the saturation curve was excluded from the analysis. Each refrigerant and thermodynamic property is treated in a similar way, so the method can be easily programmed and extended to other refrigerants.

The field of refrigerant property research has seen tremendous activity in recent years. While significant progress has been made, property models for refrigerants, particularly those for mixtures, are still under development, and the coming years promise still better models. Each model will have its own strengths and weaknesses in the future. Simpler methods, such as cubic spline curve fitting method and Helmholtz equation of state method, also have their place, provided that they are validated against data and used within their limits of applicability.

Thermodynamic properties of refrigerants calculated by using Helmholtz Equation of State given as standard equation for refrigerants in ISO17584:2005(E) by using simulation programs developed in java programming language. This equation of state requires only derivatives. Therefore it is easier to calculate compare to pressure type equation of states. The results obtained from ISO17584 EOS and a commercial package REFPROP 9.0 is compared with standard printed tables for refrigerant R1234yf, refrigerant mixture R410A and it is found that error ranges are not big. It should be not that standard printed tables might have some errors as well. Property calculations are a continuous process of improvement and error reduction. The developed programs will be presented as public access programs for everybody to use as tables and as system simulation tools in

their own system simulations.

Nomenclature

T- Temperature, K
P- Pressure, kPa
v- Specific volume, $m^3\ kg^{-1}$
s- Entropy, kj $kg^{-1}\ K^{-1}$
u- Internal Energy, kj kg^{-1}
h- Enthalpy, kj kg^{-1}
x- Quality, kg vapor (kg mix.)$^{-1}$
Cp- Specific heat for constant pressure kj $kg^{-1}\ K^{-1}$
Cp_{id}- Heat capacity of ideal gas state, kj $kg^{-1}\ K^{-1}$
Cv-Specific heat for constant volume, kj $kg^{-1}\ K^{-1}$
R- Real Gas constant, kj $kg^{-1}\ K^{-1}$
M- Molar mass, g $(mol)^{-1}$
*T**- Reducing parameter which is often equal to the critical parameter
k- Constant (1,2,…, n)
N_k- Numerical coefficients which is fitted to experimental data
α_k, β_k, ε_k, γ_k- Certain multipliers for special refrigerant (Obtained by curve fitting)
t_k, d_k, l_k, m_k- Certain upper coefficients for special refrigerant (Obtained by curve fitting)
c_k, a_k, t_k - Numerical coefficients fitted to data or derived from theoretical calculations
h_{ref}- Ideal gas reference enthalpy, kj kg^{-1}
s_{ref}- Ideal gas reference entropy, kj $kg^{-1}\ K^{-1}$
g- Gibbs free energy

Greek Symbols

τ - Dimensionless temperature variable, T^*T^{-1}
δ - Dimensionless density variable, $\rho\,\rho^{*-1}$
ρ- Density, kg m^{-3}
ρ^*- Reducing parameter which is often equal to the critical parameter
ϕ - Helmholtz equation function
ϕ_r - Real gas Helmholtz equation function
ϕ_{id} - Ideal gas Helmholtz equation function
x_i - Mole fraction of component *i* in the *n*-component mixture
ζ_{ij}, ξ_{ij} - Interaction parameters
T_i^*, ρ_i^* - Reducing parameters of pure fluids.

Subscript

id- Ideal gas behavior
r- Real gas behavior
a- Residual

Abbreviations

EOS- Equation Of State
ref- Reference
ISO- International Standard Organization
App.- Application
HEoS - Helmholtz Equation of State
CSCFM- Cubic Spline Curve Fitting Method

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