Research Article

Calculation of Thermal Pressure Coefficient of R11, R13, R14, R22, R23, R32, R41, and R113 Refrigerants by pVT Data

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For thermodynamic performance to be optimized particular attention must be paid to the fluid's thermal pressure coefficients and thermodynamic properties. A new analytical expression based on the statistical mechanics is derived for R11, R13, R14, R22, R23, R32, R41, and R113 refrigerants, using the intermolecular forces theory. In this paper, temperature dependency of the parameters of R11, R13, R14, R22, R23, R32, R41, and R113 refrigerants to calculate thermal pressure coefficients in the form of first order has been developed to second and third orders and their temperature derivatives of new parameters are used to calculate thermal pressure coefficients. These problems have led us to try to establish a function for the accurate calculation of the thermal pressure coefficients of R11, R13, R14, R22, R23, R32, R41, and R113 refrigerants based on statistical-mechanics theory for different refrigerants.

1. Introduction

Popular interest in the use of refrigerant blends started in the late 1950s. The emphasis was placed on energy savings through the reduction of irreversibility in the heat exchanger and on capacity variation during operation through the control of the fluid composition. Worldwide legislation has been enacted through the United Nations environmental program to reduce stratospheric ozone depletion. The Montreal Protocol was approved in 1987 to control production of the suspected ozone-depleting substances, among them chlorofluorocarbons and hydrochlorofluorocarbons, commonly used as refrigerants in the industry. For example, chlorofluorocarbons-(CFCs-) 11, 12 and 113 have been successfully used to determine groundwater recharge ages in the industry. Relatively good agreement exists between individual CFC ages and ages derived from other tracers [1–6].

The precise meaning of the internal pressure is contained in a generalized manner in the following well-known thermodynamic equations. United forces of external and internal pressure equalize the thermal pressure which tries to expand the matter. If the thermal pressure of a refrigerant is available, then the thermodynamics properties of refrigerant can be calculated easily. Liquids and dense fluids are usually considered

to be complicated on a molecular scale, and a satisfactory theory of liquids only began to emerge in the 1960. However, they show a number of experimental regularities, some of which have been known by theoretical basis [7–10].

The first is the internal pressure regularity, in which $((\partial E/\partial V)_T/\rho RT) V^2$ is linear with respect to ρ^2 for each isotherm, where $\rho = 1/V$ is the molar density, E is the internal energy, and V is molar volume [9]. In the internal pressure regularity, which was originally devised for normal dense fluids, is based on the cell theory and considers only nearest adjacent interaction. Lennard-Jones potential function suitably describes the interactions between the molecules of a fluid under the condition that it behaves as a normal fluid. In the internal pressure regularity was attempted to calculate the internal pressure by modeling the average configurationally potential energy and then taking its derivative with respect to volume.

The second is an expression which is driven for as the thermal pressure coefficient of dense fluids (Ar, N₂, CO, CH₄, C₂H₆, n-C₄H₁₀, iso-C₄H₁₀, C₆H₆, and C₆H₅-CH₃) [11–17]. Only, pVT experimental data have been used for the calculation of thermal pressure coefficient [18].

The third is a regularity to predict metal-nonmetal transitions in cesium fluid. An accurate empirical potential has

been found for dense cesium fluid and it is used to test the applicability of the theory. These theoretical predictions are in good agreement with experimental results [19–26].

The forth is the internal pressure of sodium, potassium, and rubidium attempt to predict X-ray diffraction and small-angle X-ray scattering to the range where the compressibility of the interacting electron gas has been theoretically predicted to become negative. Problems have led us to try to establish a function for the accurate calculation of the internal pressure and the prediction of metal-nonmetal transition alkali metals based on the internal pressure [27].

A property formulation is the set of equations used to calculate properties of a fluid at specified thermodynamic states defined by an appropriate number of independent variables. A typical thermodynamic property formulation is based on an equation of state which allows the correlation and computation of all thermodynamic properties of the fluid including properties such as entropy that cannot be measured directly. Modern equations of state at least with 17 terms for pure fluid properties are usually fundamental equations explicit in the Helmholtz energy as a function of density and temperature. The new class of equations of state for technical applications to dense fluids is formulated in the reduced Helmholtz energy. As usual, the reduced Helmholtz energy is split into one part which describes the behavior of the hypothetical ideal gas at given values of temperature and density and a second part which describes the residual behavior of the fluid. For some relevant properties the corresponding relations were given in [4, 9].

In 1993 a general regularity with 2 terms so-called the linear isotherm regularity has been reported for pure dense fluids, according to which $(Z - 1)V^2$ is linear with respect to ρ^2 , each isotherm as

$$(Z - 1)V^2 = A + B\rho^2, \quad (1)$$

where $Z \equiv pV/RT$ is the compression factor, $\rho = 1/V$ is the molar density, and A and B are the temperature-dependent parameters. This equation of state works very well for all types of dense fluids, for densities greater than the Boyle density but for temperatures below twice the Boyle temperature. The regularity was originally suggested on the basis of a simple lattice-type model applied to a Lennard-Jones (12,6) fluid [28, 29]. At present work, the regularity has been used to calculate thermal pressure coefficient of dense Trichlorofluoromethane (R11), Chlorotrifluoromethane (R13), Tetrafluoromethane (R14), Chlorodifluoromethane (R22), Trifluoromethane (R23), Difluoromethane (R32), Fluoromethane (R41), and 1,1,2-Trichloro-1,2,2-trifluoroethane (R113) refrigerants [30]. In this paper, in Section 2.1, we present a simple method that keeps first order temperature dependency of parameters in the regularity versus inverse temperature. Then, the thermal pressure coefficient is calculated by this expression. In Section 2.2, temperature dependency of parameters in the regularity has been developed to second order. In Section 2.3, temperature dependency of parameters in the regularity has been developed to third order and then the thermal pressure

coefficient is calculated in each state for R11, R13, R14, R22, R23, R32, R41, and R113 refrigerants.

2. Theory

We first test the ability of the linear isotherm regularity [18]

$$\frac{p}{\rho RT} = 1 + A\rho^2 + B\rho^4. \quad (2)$$

2.1. First Order Temperature Dependency of Parameters. We first calculate pressure by the linear isotherm regularity and then use first order temperature dependency of parameters to get the thermal pressure coefficient for the dense fluid, where

$$A = A_2 - \frac{A_1}{RT}, \quad (3)$$

$$B = \frac{B_1}{RT}. \quad (4)$$

Here A_1 and B_1 are related to the intermolecular attractive and repulsive forces, respectively, while A_2 is related to the nonideal thermal pressure and RT has its usual meaning.

In the present work, the starting point in the derivation is (2). By substitution of (3) and (4) in (2) we obtain the pressure for R11, R13, R14, R22, R23, R32, R41, and R113 fluids:

$$p = \rho RT + A_2\rho^3 RT - A_1\rho^3 + B_1\rho^5. \quad (5)$$

We first drive an expression for thermal pressure coefficient using first order temperature dependency of parameters. The final result is TPC⁽¹⁾:

$$\left(\frac{\partial p}{\partial T}\right)_\rho = R\rho + A_2 R\rho^3. \quad (6)$$

According to (6), the experimental value of density and value of A_2 from Table 1 can be used to calculate the value of thermal pressure coefficient.

For this purpose we have plotted A versus $1/T$ whose intercept shows value of A_2 . Table 1 shows the A_2 values for R11, R13, R14, R22, R23, R32, R41, and R113 fluids [1, 6, 30].

Then we obtain the thermal pressure coefficient of dense fluids. R13 serves as our primary test fluid because of the abundance of available thermal pressure coefficients data [6, 30]. For this purpose we have plotted A versus $1/T$ whose intercept shows value of A_2 . Figures 1(a) and 1(b) show plots of A and B versus inverse temperature for R13, respectively. It is clear that A and B versus inverse temperature are not first order.

2.2. Second Order Temperature Dependency of Parameters. In order to solve this problem, the linear isotherm regularity equation of state in the form of truncated temperature series of A and B parameters has been developed to second order for dense fluids. Figures 1(a) and 1(b) show plots of A and B parameters versus inverse temperature for R13 fluid. It is clear that A and B versus inverse temperature are second order.

FIGURE 1: (a) Plot of A versus inverse temperature. Red and blue lines are the first and second order fit to the A data points, for R13, respectively. (b) Plot of B versus inverse temperature. Red and blue lines are the first and second order fit to the B data points, for R13, respectively.

TABLE 1: The calculated values of A_2 for different fluids using (3) and the coefficient of determination (R^2) [1, 6, 18, 30].

Fluid	A_2	$(T_{\min} - T_{\max})/K$	R^2
R11	2.2109	180–500	0.9849
R13	1.5748	100–370	0.9946
R14	1.1315	150–310	0.9894
R22	1.5616	120–500	0.9890
R23	1.0286	150–450	0.9905
R32	0.8650	150–430	0.9909
R41	0.6263	180–410	0.9927
R113	1.3863	300–525	0.9977

TABLE 2: The calculated values of A_1, A_3 using (7) and B_1, B_3 using (8) for different fluids and the coefficient of determination (R^2) [1, 6, 18, 30].

Fluid	A_1	A_3	R^2	B_1	B_3	R^2
R11	0.1354	-1.7517×10^5	0.9987	0.0625	1.4777×10^4	0.9997
R13	1.3594	-7165.5660	0.9898	-0.0650	-610.8607	0.9951
R14	0.1810	-4.2972×10^4	0.9992	0.1072	5461.0737	0.9997
R22	0.6210	-4.8725×10^4	0.9983	0.0196	3298.4237	0.9994
R23	0.4457	-3.4069×10^4	0.9993	0.0317	2449.0303	0.9997
R32	0.2404	-3.8638×10^4	0.9980	0.0528	3251.8493	0.9996
R41	0.0924	-3.7820×10^4	0.9982	0.0850	4669.1360	0.9996
R113	0.6053	-1.2415×10^5	0.9992	0.0316	7746.1673	0.9997

Thus, we obtain extending parameters A and B resulting in second order equation as follows:

$$A = A_1 + \frac{A_2}{T} + \frac{A_3}{T^2}, \quad (7)$$

$$B = B_1 + \frac{B_2}{T} + \frac{B_3}{T^2}. \quad (8)$$

The starting point in the derivation is (2) again. By substitution of (7)-(8) in equation (2) we obtain the pressure for R11, R13, R14, R22, R23, R32, R41, and R113 fluids [1, 6, 30]:

$$p = \rho RT + A_1 \rho^3 RT + A_2 \rho^3 R + \frac{A_3 \rho^3 R}{T} + B_1 \rho^5 RT + B_2 \rho^5 R + \frac{B_3 \rho^5 R}{T}. \quad (9)$$

First, second, and third temperature coefficients and their temperature derivatives were calculated from this model and

the final result is for the thermal pressure coefficient to form TPC⁽²⁾:

$$\left(\frac{\partial p}{\partial T} \right)_\rho = \rho R + A_1 \rho^3 R - \frac{A_3 \rho^3 R}{T^2} + B_1 \rho^5 R - \frac{B_3 \rho^5 R}{T^2}. \quad (10)$$

As (10) shows, it is possible to calculate the thermal pressure coefficient at each density and temperature by knowing A_1, A_3, B_1, B_3 . For this purpose we have plotted extending parameters of A and B versus $1/T$ whose intercept and coefficients show the values of A_1, A_3, B_1, B_3 that are given in Table 2.

2.3. Third Order Temperature Dependency of Parameters. In another step, we test to form truncated temperature series of A and B parameters to third order:

$$A = A_1 + \frac{A_2}{T} + \frac{A_3}{T^2} + \frac{A_4}{T^3}, \quad (11)$$

$$B = B_1 + \frac{B_2}{T} + \frac{B_3}{T^2} + \frac{B_4}{T^3}. \quad (12)$$

TABLE 3: The calculated values of A_1, A_3, A_4 using (11) and B_1, B_3, B_4 using (12) for different fluids and the coefficient of determination (R^2) [1, 6, 18, 30].

Fluid	A_1	A_3	A_4	R^2	B_1	B_3	B_4	R^2
R11	-1.1003	-5.2851×10^5	3.2477×10^7	0.9999	0.3293	9.1064×10^4	-7.0120×10^5	0.9999
R13	-1.2784	-2.9997×10^5	1.5854×10^7	0.9999	0.2582	9.5263×10^4	-1.9424×10^6	0.9999
R14	0.8257	4.5033×10^4	-5.9456×10^6	0.9998	0.0642	-402.0298	3.6911×10^5	0.9993
R22	8.1×10^{-3}	-1.5322×10^5	6.9130×10^6	0.9999	0.0988	1.6789×10^4	-8.9251×10^5	0.9998
R23	0.2352	-7.5616×10^4	3.1780×10^6	0.9998	0.0618	8402.7408	-4.5542×10^5	0.9993
R32	-0.1924	-1.2103×10^5	6.2039×10^6	0.9999	0.1290	1.7760×10^4	-1.0925×10^6	0.9995
R41	0.6315	8.2985×10^4	-1.0303×10^7	0.9999	0.0298	-7705.9129	1.0555×10^6	0.9988
R113	-0.9445	-8.5187×10^5	9.2993×10^7	0.9998	0.2258	9.8942×10^4	-1.1654×10^7	0.9995

FIGURE 2: The experimental values of thermal pressure coefficient versus density for R13 fluid are compared with thermal pressure coefficient using the $TPC^{(1)}$, $TPC^{(2)}$, and $TPC^{(3)}$ at 300 K.

FIGURE 3: The experimental values of thermal pressure coefficient versus density for R13 fluid are compared with thermal pressure coefficient using the $TPC^{(1)}$, $TPC^{(2)}$, and $TPC^{(3)}$ at 320 K.

The starting point in the derivation is (2) again. By substitution of (11) and (12) in (2) we obtain the pressure equation for R11, R13, R14, R22, R23, R32, R41, and R113 fluids [1, 6, 30]:

$$p = \rho RT + A_1 \rho^3 RT + A_2 \rho^3 R + \frac{A_3 \rho^3 R}{T} + \frac{A_4 \rho^3 R}{T^2} + B_1 \rho^5 RT + B_2 \rho^5 R + \frac{B_3 \rho^5 R}{T} + \frac{B_4 \rho^5 R}{T^2}. \quad (13)$$

The final result is for the thermal pressure coefficient to form $TPC^{(3)}$:

$$\left(\frac{\partial p}{\partial T} \right)_\rho = \rho R + A_1 \rho^3 R - \frac{A_3 \rho^3 R}{T^2} - \frac{2A_4 \rho^3 R}{T^3} + B_1 \rho^5 R - \frac{B_3 \rho^5 R}{T^2} - \frac{2B_4 \rho^5 R}{T^3}. \quad (14)$$

Based on (14), to obtain the thermal pressure coefficient, it is necessary to determine values $A_1, A_3, A_4, B_1, B_3, B_4$ these values are given in Table 3. In contrast, Figures 2 and 3 show the experimental values of the thermal pressure coefficient versus density for R13 of liquid and supercritical fluids that are compared with the thermal pressure coefficient using the $TPC^{(1)}$, $TPC^{(2)}$, and $TPC^{(3)}$ at 300 and 320 K, respectively.

3. Experimental Tests and Discussion

A compromised ozone layer results in increased ultraviolet (UV) radiation reaching the earth's surface, which can have wide ranging health effects. Global climate change is believed to be caused by buildup of greenhouse gases in the atmosphere. The primary greenhouse gas is carbon dioxide (CO_2), created by fossil fuel-burning power plants.

FIGURE 4: The experimental values of thermal pressure coefficient versus density for R11 fluid are compared with thermal pressure coefficient using the $TPC^{(1)}$, $TPC^{(2)}$, and $TPC^{(3)}$ at 400 K.

These gases trap the earth's heat, causing global warming. CFC, HCFC, and HFC refrigerants are considered greenhouse gases. The accurate description of thermodynamic properties of fluids over the large intervals of temperatures and densities with multiparameter equations of state has been a subject of active research, which has developed continuously during the last 30 years and will continue to do so. Generally, three categories of equations of state can be established according to their fundamentals: empirical, theoretical, and semiempirical. An empirical equation of state is usually needed to several experimental data or many adjustable parameters and therefore their applications are usually restricted to a very limited number of substances. A theoretical equation of state is also needed to the same number of molecular parameters, particularly to the intermolecular pair potential function [1–6, 30].

In this work, the thermal pressure coefficient is computed for refrigerant fluids of liquid and super critical fluids using three different models of the theoretical equation of state. R13 serves as our primary test fluid because of the abundance of available thermal pressure coefficients data. Such data are more limited for the other fluids examined. When we restricted temperature series of A and B parameters to first order it has been seen that the points from the low densities for $TPC^{(1)}$ deviate significantly from the experimental data. To decrease adequately deviation the thermal pressure coefficient from the experimental data, it was necessary to extend the temperature series of A and B parameters to second order. The present approach to

FIGURE 5: The experimental values of thermal pressure coefficient versus density for R11 fluid are compared with thermal pressure coefficient using the $TPC^{(1)}$, $TPC^{(2)}$, and $TPC^{(3)}$ at 420 K.

TABLE 4: Comparison of $(\partial p/\partial T)_\rho$ among the calculated and experimental values for R11 at 400 K [1, 18, 30].

p/MPa	$\rho/\text{mol}\cdot\text{L}^{-1}$	$(\partial p/\partial T)_\rho (\text{MPa}\cdot\text{K}^{-1})$			
		$TPC^{\text{Helmholtz}}$	$TPC^{(1)}$	$TPC^{(2)}$	$TPC^{(3)}$
1.4074	8.6318	0.3834	0.7986	0.4312	0.4310
2.1000	8.6827	0.3948	0.8120	0.4375	0.4375
3.1000	8.7509	0.4065	0.8301	0.4460	0.4462
4.1000	8.8142	0.4174	0.8472	0.4539	0.4544
5.1000	8.8732	0.4276	0.8633	0.4614	0.4621
6.1000	8.9286	0.4373	0.8787	0.4685	0.4694
7.1000	8.9810	0.4465	0.8933	0.4753	0.4764
8.1000	9.0306	0.4554	0.9074	0.4818	0.4831
9.1000	9.0780	0.4638	0.9210	0.4880	0.4895
10.1000	9.1232	0.4719	0.9340	0.4940	0.4957
11.1000	9.1665	0.4797	0.9467	0.4998	0.5017
12.1000	9.2081	0.4872	0.9589	0.5053	0.5075
13.1000	9.2481	0.4945	0.9708	0.5107	0.5131
14.1000	9.2868	0.5015	0.9824	0.5160	0.5185
15.1000	9.3241	0.5083	0.9937	0.5211	0.5238
16.1000	9.3602	0.5149	1.0046	0.5260	0.5289
17.1000	9.3952	0.5214	1.0154	0.5309	0.5339
18.1000	9.4292	0.5277	1.0259	0.5356	0.5388
19.1000	9.4623	0.5338	1.0361	0.5402	0.5436
20.1000	9.4944	0.5398	1.0462	0.5447	0.5483
21.1000	9.5257	0.5456	1.0560	0.5491	0.5529
22.1000	9.5562	0.5513	1.0657	0.5534	0.5574
23.1000	9.5859	0.5569	1.0752	0.5576	0.5618
24.1000	9.6150	0.5624	1.0845	0.5617	0.5661
25.1000	9.6434	0.5678	1.0937	0.5658	0.5703

TABLE 5: Comparison of $(\partial p/\partial T)_\rho$ among the calculated and experimental values for R11 at 440 K [1, 18, 30].

p/MPa	$\rho/\text{mol}\cdot\text{L}^{-1}$	$(\partial p/\partial T)_\rho (\text{MPa}\cdot\text{K}^{-1})$			
		TPC ^{Helmholtz}	TPC ⁽¹⁾	TPC ⁽²⁾	TPC ⁽³⁾
2.7745	7.3336	0.2189	0.5067	0.2614	0.2515
3.1000	7.4066	0.2271	0.5208	0.2679	0.2581
4.1000	7.5898	0.2486	0.5572	0.2846	0.2755
5.1000	7.7349	0.2664	0.5873	0.2983	0.2899
6.1000	7.8569	0.2818	0.6135	0.3102	0.3024
7.1000	7.9630	0.2955	0.6369	0.3207	0.3137
8.1000	8.0576	0.3080	0.6582	0.3304	0.3240
9.1000	8.1431	0.3195	0.6779	0.3392	0.3335
10.1000	8.2215	0.3302	0.6964	0.3475	0.3424
11.1000	8.2941	0.3403	0.7138	0.3552	0.3509
12.1000	8.3617	0.3498	0.7302	0.3626	0.3589
13.1000	8.4251	0.3587	0.7459	0.3695	0.3665
14.1000	8.4850	0.3673	0.7609	0.3762	0.3738
15.1000	8.5417	0.3755	0.7753	0.3826	0.3808
16.1000	8.5956	0.3833	0.7892	0.3887	0.3876
17.1000	8.6470	0.3909	0.8026	0.3946	0.3942
18.1000	8.6962	0.3981	0.8155	0.4003	0.4005
19.1000	8.7434	0.4052	0.8281	0.4058	0.4067
20.1000	8.7887	0.4120	0.8403	0.4112	0.4127
21.1000	8.8324	0.4185	0.8521	0.4164	0.4186
22.1000	8.8746	0.4249	0.8637	0.4215	0.4243
23.1000	8.9153	0.4312	0.8750	0.4264	0.4298
24.1000	8.9547	0.4372	0.8860	0.4312	0.4353
25.1000	8.9930	0.4431	0.8967	0.4359	0.4406
26.1000	9.0301	0.4489	0.9073	0.4404	0.4458

obtaining the thermal pressure coefficient from pVT data contrasts with the experimental data by extending the temperature series of A and B parameters to second order and its derivatives. That, the thermal pressure coefficient give to form TPC⁽²⁾.

We also considered an even more accurate estimates namely, the extension of temperature series of A and B parameters to third order. The final result is for the thermal pressure coefficient to form TPC⁽³⁾. In contrast, Figures 4 and 5 show the experimental values of the thermal pressure coefficient versus density for R11 of liquid fluid that are compared with the thermal pressure coefficient using the TPC⁽¹⁾, TPC⁽²⁾, and TPC⁽³⁾ at 400 and 440 K, respectively. Also, the experimental and calculated values of the thermal pressure coefficient using the TPC⁽¹⁾, TPC⁽²⁾, and TPC⁽³⁾ are compared in Tables 4, 5, 6, and 7 for R13 and R11 fluids. Although all three models capture the qualitative features for refrigerants, the calculated values of the thermal pressure coefficient using the TPC⁽²⁾ model produce quantitative agreement, but Tables 4, 5, 6, and 7, which is a more test of these models, shows that the TPC⁽³⁾ model is able to accurately predict both the thermal pressure coefficient of the liquid and the supercritical refrigerants.

TABLE 6: Comparison of $(\partial p/\partial T)_\rho$ among the calculated and experimental values for R13 at 300 K [1, 6, 18, 30].

p/MPa	$\rho/\text{mol}\cdot\text{L}^{-1}$	$(\partial p/\partial T)_\rho (\text{MPa}\cdot\text{K}^{-1})$			
		TPC ^{Helmholtz}	TPC ⁽¹⁾	TPC ⁽²⁾	TPC ⁽³⁾
8.0000	10.0570	0.3095	0.5114	0.4231	0.3317
9.0000	10.2590	0.3295	0.5393	0.4434	0.3490
10.0000	10.4330	0.3476	0.5643	0.4614	0.3645
11.0000	10.5870	0.3642	0.5870	0.4776	0.3786
12.0000	10.7260	0.3796	0.6081	0.4925	0.3917
13.0000	10.8520	0.3940	0.6276	0.5061	0.4038
14.0000	10.9680	0.4075	0.6460	0.5189	0.4152
15.0000	11.0750	0.4203	0.6633	0.5309	0.4260
16.0000	11.1750	0.4324	0.6797	0.5421	0.4362
17.0000	11.2700	0.4440	0.6956	0.5530	0.4461
18.0000	11.3580	0.4550	0.7106	0.5631	0.4554
19.0000	11.4430	0.4656	0.7252	0.5729	0.4645
20.0000	11.5230	0.4757	0.7392	0.5823	0.4732
21.0000	11.5990	0.4854	0.7526	0.5912	0.4816
22.0000	11.6720	0.4948	0.7657	0.5999	0.4898
23.0000	11.7420	0.5038	0.7784	0.6082	0.4977
24.0000	11.8090	0.5125	0.7907	0.6163	0.5054
25.0000	11.8740	0.5208	0.8027	0.6242	0.5129
26.0000	11.9360	0.5290	0.8143	0.6317	0.5202
27.0000	11.9970	0.5368	0.8258	0.6391	0.5274
28.0000	12.0550	0.5444	0.8369	0.6463	0.5343
29.0000	12.1120	0.5517	0.8479	0.6533	0.5412
30.0000	12.1660	0.5587	0.8584	0.6600	0.5478
31.0000	12.2200	0.5657	0.8689	0.6667	0.5544
32.0000	12.2720	0.5723	0.8792	0.6732	0.5609

4. Result

Refrigerants are the working fluids in refrigeration, air-conditioning, and heat-pumping systems. Accurate and comprehensive thermodynamic properties of refrigerants such as the thermal pressure coefficients are in demand by both producers and users of the materials. However, the database for the thermal pressure coefficients is small at present. Furthermore, the measurements of the thermal pressure coefficients made by different researchers often reveal systematic differences between their estimates. The researchers have led us to try to establish a correlation function for the accurate calculation of the thermal pressure coefficients for different fluids over a wide temperature and pressure ranges. The most straightforward way to derive the thermal pressure coefficient is the calculation of the thermal pressure coefficient with the use of the principle of corresponding states which covers wide temperature and pressure ranges. The principle of corresponding states calls for reducing the thermal pressure at a given reduced temperature and density to be the same for all fluids. The leading term of this correlation function is the thermal pressure coefficient of perfect gas, which each gas obeys in the low density range [31, 32].

TABLE 7: Comparison of $(\partial p/\partial T)_\rho$ among the calculated and experimental values for R13 at 320 K [1, 6, 18, 30].

p/MPa	$\rho/\text{mol}\cdot\text{L}^{-1}$	$(\partial p/\partial T)_\rho (\text{MPa}\cdot\text{K}^{-1})$			
		TPC ^{Helmholtz}	TPC ⁽¹⁾	TPC ⁽²⁾	TPC ⁽³⁾
15.0000	10.1650	0.3269	0.5262	0.4304	0.3063
16.0000	10.3040	0.3400	0.5457	0.4444	0.3175
17.0000	10.4310	0.3523	0.5640	0.4574	0.3281
18.0000	10.5490	0.3640	0.5813	0.4696	0.3381
19.0000	10.6600	0.3751	0.5980	0.4813	0.3479
20.0000	10.7630	0.3857	0.6138	0.4922	0.3571
21.0000	10.8610	0.3959	0.6290	0.5028	0.3660
22.0000	10.9530	0.4056	0.6436	0.5128	0.3746
23.0000	11.0410	0.4149	0.6578	0.5224	0.3829
24.0000	11.1240	0.4239	0.6713	0.5316	0.3909
25.0000	11.2040	0.4326	0.6846	0.5406	0.3988
26.0000	11.2810	0.4409	0.6975	0.5492	0.4064
27.0000	11.3540	0.4490	0.7099	0.5575	0.4138
28.0000	11.4250	0.4568	0.7221	0.5656	0.4211
29.0000	11.4930	0.4643	0.7339	0.5734	0.4282
30.0000	11.5590	0.4716	0.7455	0.5811	0.4352
31.0000	11.6220	0.4786	0.7567	0.5884	0.4419
32.0000	11.6840	0.4855	0.7679	0.5957	0.4486
33.0000	11.7440	0.4921	0.7788	0.6027	0.4552
34.0000	11.8020	0.4986	0.7894	0.6096	0.4616
35.0000	11.8580	0.5048	0.7997	0.6163	0.4679

In this paper, we drive an expression for the thermal pressure coefficient of R11, R13, R14, R22, R23, R32, R41, and R113 dense refrigerants using the linear isotherm regularity [18, 28]. Unlike previous models, it has been shown in this work that the thermal pressure coefficient can be obtained without employing any reduced Helmholtz energy [9]. Only pVT experimental data have been used for the calculation of the thermal pressure coefficient of R11, R13, R14, R22, R23, R32, R41, and R113 refrigerants [8]. Comparison of the calculated values of the thermal pressure coefficient using the linear isotherm regularity with the values obtained experimentally shows the validity of the use of the linear isotherm regularity for studying the thermal pressure coefficient of R11, R13, R14, R22, R23, R32, R41, and R113 refrigerants. In this work, it has been shown that the temperature dependences of the intercept and slope of using linear isotherm regularity are nonlinear. This problem has led us to try to obtain the expression for the thermal pressure coefficient of R11, R13, R14, R22, R23, R32, R41, and R113 refrigerants by extending the intercept and slope of the linearity parameters versus inversion of temperature to the third order. The thermal pressure coefficients predicted from this simple model are in good agreement with experimental data. The results show the accuracy of this method is generally quit good. The resulting model predicts accurately the thermal pressure coefficients from the lower density limit at the Boyle density from triple temperature up to about double the Boyle temperature. The upper density limit appears to be reached at 1.4 times the Boyle density. These problems have led us to try to establish a function for

the accurate calculation of the thermal pressure coefficients based on equation of state theory for different refrigerants.

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