Practical Expressions for Thermodynamic and Transport Properties of Commonly Used Fluids

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Expressions available in the field of fluid applications have been obtained which readily yield thermophysical property values, dependent on temperature or on temperature and pressure, for saturated fluids or compressed liquids of technical importance.

Nomenclature

A = constant defined in Eqs. (5a) or (8a), or coefficient of Eqs. (23a–26a)
a = coefficient of Eqs. (9b), (9c), (10), (12a), (12b), (13a), (13b), (14a), (15), (16a–16c), (17), (18a–18d), (19), (20a), (20b)
a, b, c, d, e = coefficients of Eq. (9a)
B = constant defined in Eqs. (5b) or (8b)
c = solution of Eq. (4), or coefficient of Eqs. (21), (22), (23b–26b)
c_p = specific heat at constant pressure, J/kg·K
E = error defined in Eqs. (3) or (7)
f, g = relations expressed as Eqs. (2) or (6)
h = specific enthalpy, J/kg
K = number of coefficients
k = thermal conductivity, W/m·K
M = molecular weight, kg/mol
N = number of data
n = exponent of Eqs. (21) or (22)
P = 1 or 2, power multiplier in Eqs. (16c) or (18d)
p = pressure, MPa
R = universal gas constant, 8.31696 J/mol·K
T = temperature, K
w = dimensionless fluid property
γ = specific heat ratio
ε_{STD} = standard deviation
λ = latent heat of vaporization, J/kg
μ = dynamic viscosity, Pa·s
ρ = density, kg/m^3
σ = surface tension, N/m

Subscripts

0 = reference value
0, 1, 2, 3, 4 = numbers specifying coefficients
c = critical value
j, k = numbers specifying matrix or array elements
L = saturated liquid
n = number specifying data
Q = compressed liquid
r = reduced value, defined in Eq. (1)
V = saturated vapor

Introduction

SINCE active temperature control and higher heat rejection are often requested for various types of spacecraft, heat pipes and fluid loop systems have become more important than ever. For their design practice, there is a need for thermophysical property data of working fluids or coolants of interest. Most of the data are already given in the literature,[1,2] and some of them are reduced to empirical formulas[10,13] calculating property values. However, their mathematical forms are not always suited to engineering calculations. Also, for a certain property of fluids one finds so far no relationship between property data and temperature. Practical expressions are, therefore, needed which would permit a precise evaluation of thermophysical properties of saturated fluids or compressed liquids.

Fluids considered here are Freons (R11, R12, R13B1, R21, R22, R113, R114, and R502), ammonia, water, methanol, ethanol, propane, and acetone; all of which are commonly used as coolants or in heat pipes. A linear regression analysis employing the least square method has been made on property data of the above 14 saturated fluids. As a result of the analysis, new or improved expressions are obtained for vapor pressure, liquid density, liquid/vapor specific heat, vapor specific heat ratio, liquid/vapor thermal conductivity, liquid/vapor dynamic viscosity, liquid/vapor specific enthalpy, latent heat of vaporization, and liquid surface tension. Then, for Freons, ammonia, and water at compressed liquid phase, presented in this paper is new correction formulas from which density, specific heat, thermal conductivity, and viscosity are evaluated.

Method of Calculations

With a view to facilitating data reduction and also to obtaining more general expressions, one introduces the reduced temperature and the reduced pressure

$$T_r = T/T_c \tag{1a}$$

$$p_r = p/p_c \tag{1b}$$

where T is the temperature expressed in K, p the pressure expressed in MPa, T_c the critical temperature, and p_c the critical pressure. The values of T_c and p_c are listed in the left-hand column of Table 1.

Since thermophysical properties of saturated fluids merely depend on temperature, all of them will have a functional relation as

$$g(w) = \sum_{k=1}^{K} c_k f_k(T_r) \tag{2}$$

where w is the dimensionless property value, c_k the coefficient to be determined, K the number of coefficients, and f_k and g are the functions of which the forms can empirically be specified. According to the least square method, an optimal

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value of c_k is obtained in such a way as to minimize the following expression:

$$E = \sum_{n=1}^{N} \left[\sum_{k=1}^{K} c_k f_k(T_{rn}) - g(w_n) \right]^2 \quad (3)$$

where N is the number of data and one has N set of data (T_{rn}, w_n). The result of minimization of Eq. (3) is written as

$$\sum_{k=1}^{K} A_{jk} c_k = B_j \; (j = 1, 2, \ldots, K) \quad (4)$$

where A_{jk} and B_j are

$$A_{jk} = \sum_{n=1}^{N} f_j(T_{rn}) f_k(T_{rn}) \quad (5a)$$

$$B_j = \sum_{n=1}^{N} f_j(T_{rn}) g(w_n) \quad (5b)$$

Then, thermophysical properties of compressed liquids depend on both temperature and pressure. One, therefore, has a relation similar to Eq. (2)

$$g(w) = \sum_{k=1}^{K} c_k f_k(T_r, p_r) \quad (6)$$

An object function corresponding to Eq. (3) is

$$E = \sum_{n=1}^{N} \left[\sum_{k=1}^{K} c_k f_k(T_{rn}, p_{rn}) - g(w_n) \right]^2 \quad (7)$$

where one has N set of data (T_{rn}, p_{rn}, w_n). The result of minimization of Eq. (7) is also written as Eq. (4), but A_{jk} and B_j become

$$A_{jk} = \sum_{n=1}^{N} f_j(T_{rn}, p_{rn}) f_k(T_{rn}, p_{rn}) \quad (8a)$$

$$B_j = \sum_{n=1}^{N} f_j(T_{rn}, p_{rn}) g(w_n) \quad (8b)$$

Results and Discussion

Computations based upon Eq. (4) and Eqs. (5) or (8) have been carried out for a large number of data sets, (T_{rn}, w_n) or (T_{rn}, p_{rn}, w_n), collected from the literature.[2–12] In this connection, of prime importance are mathematical forms selected as $f_k(T_r)$ and $g(w)$ in Eq. (2) or as $f_k(T_r, p_r)$ and $g(w)$ in Eq. (6). Most of them originate from expressions already tested in the past, but some have been proposed by the author. All the expressions considered here are shown in the following. The correlation errors are then mentioned in the tables.

Although there are several empirical formulas on saturated vapor pressure, p_V, commonly used are the following two:

$$\ln (p_V/p_c) = a + b/T_r + c \ln T_r + dT_r + eT_r^2 \quad (9a)$$

$$\ln (p_V/p_c) = a_0 + a_1/T_r + a_2/T_r^2 \quad (9b)$$

The forms of Eqs. (9a) and (9b) were, respectively, proposed by Van Laar[14] and by Thodos.[15] An extended Thodos's formula

$$\ln (p_V/p_c) = a_0 + a_1/T_r + a_2/T_r^2 + a_3/T_r^3 \quad (9c)$$

Table 1 Coefficient values in Eq. (9b) for saturated vapor pressure expressed in MPa

	T_c, K	p_c, MPa	a_0	a_1	a_2	T_r	ε_{STD}	N	Ref.
R11	471.2	4.409	5.3182	−4.8265	−0.56899	0.44–0.85	0.39	21	2
R12	385.0	4.136	5.5852	−5.2034	−0.42589	0.55–0.94	0.39	21	2
R13B1	340.1	3.957	6.0280	−5.9025	−0.14540	0.63–0.97	0.41	21	2
R21	451.6	5.184	5.4131	−4.8658	−0.60804	0.48–0.80	0.089	21	2
R22	369.3	4.988	5.9652	−5.6310	−0.35962	0.62–0.95	0.24	21	2
R113	487.5	3.411	5.4671	−4.8113	−0.72299	0.49–0.80	0.098	21	2
R114	418.9	3.263	5.5389	−4.9203	−0.68536	0.52–0.82	0.056	21	2
R502	355.3	4.27	5.6903	−5.2858	−0.48655	0.60–0.93	0.11	21	2
Ammonia	405.6	11.28	6.1284	−5.7678	−0.37997	0.49–0.97	0.57	21	2
Water	647.3	22.12	6.1160	−5.5899	−0.60032	0.42–0.73	0.12	21	2
Methanol	512.6	8.10	7.1551	−6.4084	−0.78724	0.50–0.88	0.28	21	2
Ethanol	516.2	6.38	7.0099	−5.8633	−1.1791	0.52–0.90	0.82	21	2
Propane	369.8	4.250	5.8404	−5.6823	−0.18982	0.63–0.88	0.20	21	2
Acetone	508.2	4.70	7.8175	−7.6271	0.061506	0.45–0.82	6.3	10	3

Table 2 Coefficient values in Eq. (10) with $\rho_{L0} = 10^3$ kg/m^3 for saturated liquid density expressed in kg/m^3

	a_0	a_1	a_2	a_3	a_4	T_r	ε_{STD}	N	Ref.
R11	−0.32754	6.2179	−11.145	11.006	−3.7105	0.44–0.85	0.018	21	2
R12	0.76234	−0.75319	5.5328	−6.5323	3.1340	0.55–0.94	0.004	21	2
R13B1	0.67184	2.0778	−2.0808	3.5487	−1.5341	0.63–0.97	0.016	21	2
R21	2.9179	−13.386	32.456	−32.106	12.207	0.48–0.80	0.032	21	2
R22	0.50872	1.0061	0.18511	0.13519	0.11857	0.62–0.95	0.003	21	2
R113	0.56032	0.99819	0.96279	−1.3882	1.0568	0.49–0.80	0.002	21	2
R114	0.85450	−0.57502	3.9530	−3.5130	1.4145	0.52–0.82	0.003	21	2
R502	1.0789	−2.6943	9.9848	−11.026	4.8288	0.60–0.93	0.061	21	2
Ammonia	0.24826	0.28170	0.65884	−0.57148	0.31403	0.49–0.97	0.013	21	2
Water	−21.022	121.41	−255.96	242.02	−85.965	0.42–0.73	0.32	21	2
Methanol	1.2257	−6.4270	18.969	−21.871	9.2908	0.50–0.88	0.029	21	2
Ethanol	2.0227	−11.089	28.896	−30.959	12.280	0.52–0.91	0.078	21	2
Propane	0.16903	0.54900	0.33454	−0.95927	0.70452	0.63–0.88	0.005	21	2
Acetone	4.3123	−23.263	52.423	−50.906	18.692	0.45–0.82	0.32	10	3

was also examined. With regard to accuracy, Eqs. (9a) and (9c) are better than Eq. (9b) but they make little difference in engineering calculations. The use of Eq. (9b) is recommended because of it being less in the number of coefficients than Eqs. (9a) and (9c). The coefficient values in Eq. (9b) are given in the right half of Table 1.

With regard to saturated liquid density, ρ_L, there is an expression suggested by Martin[16] and employed by Yen and Woods[17]

$$\rho_L/\rho_{L0} = a_0 + a_1(1 - T_r)^{1/3} + a_2(1 - T_r)^{2/3} + a_3(1 - T_r) + a_4(1 - t_r)^{4/3} \quad (10)$$

where ρ_L and ρ_{L0} are expressed in kg/m^3. The coefficient values in Eq. (10) are given in Table 2 where $\rho_{L0} = 10^3$ kg/m^3. Saturated vapor density, ρ_V, can now be derived from Clapeyron-Clausius's formula

$$1/\rho_V = 1/\rho_L + \lambda/T(dp_V/dT) \quad (11)$$

where λ is the latent heat of vaporization.

Specific heat at constant pressure of saturated liquid and that of saturated vapor, c_{pL} and c_{pV}, have usually been evaluated in positive power series expansion

$$c_{pL}/c_{pL0} = a_0 + a_1T_r + a_2T_r^2 + a_3T_r^3 + a_4T_r^4 \quad (12a)$$

$$c_{pV}/c_{pV0} = a_0 + a_1T_r + a_2T_r^2 + a_3T_r^3 + a_4T_r^4 \quad (13a)$$

where c_{pL}, c_{pL0}, c_{pV}, and c_{pV0} are expressed in J/kg·K. However, the following new expressions:

$$c_{pL}/c_{pL0} = a_0 + a_1/(1 - T_r) + a_2/(1 - T_r)^2 + a_3/(1 - T_r)^3 \quad (12b)$$

$$c_{pV}/c_{pV0} = a_0 + a_1/(1 - T_r) + a_2/(1 - T_r)^2 + a_3/(1 - T_r)^3 \quad (13b)$$

can evaluate c_{pL} and c_{pV} with smaller errors than Eqs. (12a) and (13a). Also, specific heat ratio of saturated vapor, γ_V, is expressed as

$$\gamma_V = a_0 + a_1/(1 - T_r) + a_2/(1 - T_r)^2 \quad (14a)$$

The accuracy of Eq. (14a) is better than that of the thermodynamically derived expression

$$\gamma_V = c_{pV}/(c_{pV} - \bar{R}/\bar{M}) \quad (14b)$$

where $\bar{R}$ is the universal gas constant, 8.31696 J/mol·K and $\bar{M}$ the molecular weight expressed in kg/mol. The coefficient values in Eqs. (12b), (13b), and (14a) are given in Tables 3, 4, and 5, respectively, where $c_{pL0} = c_{pV0} = 10^3$ J/kg·K.

An expression commonly used for thermal conductivity of saturated liquid and that of saturated vapor, k_L and k_V, are of positive power series expansion

$$k_L/k_{L0} = a_0 + a_1T_r + a_2T_r^2 + a_3T_r^3 \quad (15)$$

$$k_V/k_{V0} = a_0 + a_1T_r + a_2T_r^2 + a_3T_r^3 \quad (16a)$$

where k_L, k_{L0}, k_V, and k_{V0} are expressed in W/m·K. For some fluids, Eq. (16a) does not yield a good estimate of k_V. In such cases, one finds that the following even power series expansion

$$k_V/k_{V0} = a_0 + a_2T_r^2 + a_4T_r^4 + a_6T_r^6 + a_8T_r^8 \quad (16b)$$

Table 3 Coefficient values in Eq. (12b) with $c_{pL0} = 10^3$ J/kg·K for specific heat, expressed in J/kg·K, at constant pressure of saturated liquid

	a_0	a_1	a_2	a_3	T_r	ε_{STD}	N	Ref.
R11	0.62274	0.12823	$-0.63118\cdot10^{-2}$	$-0.19610\cdot10^{-2}$	0.44–0.64	0.030	11	2
R12	0.77805	0.039826	$0.11540\cdot10^{-2}$	$-0.80438\cdot10^{-4}$	0.55–0.94	0.45	21	2
R13B1	0.39730	0.13690	−0.015950	$0.78813\cdot10^{-3}$	0.60–0.89	0.22	21	2
R21	0.80743	0.14104	−0.024033	$0.15225\cdot10^{-2}$	0.60–0.83	0.11	11	4
R22	1.0901	−0.068817	0.034425	$-0.29039\cdot10^{-2}$	0.51–0.79	0.026	21	2
R113	0.35738	0.37879	−0.072276	$0.51174\cdot10^{-2}$	0.49–0.77	0.13	11	4
R114	0.021662	0.58475	−0.11223	$0.77116\cdot10^{-2}$	0.52–0.82	0.072	21	2
R502	0.73834	0.15464	−0.014036	$0.44786\cdot10^{-3}$	0.60–0.93	0.28	21	2
Ammonia	3.9405	0.21405	$0.30383\cdot10^{-2}$	$-0.75273\cdot10^{-4}$	0.49–0.97	1.3	21	2
Water	5.4699	−1.5378	0.57043	−0.61301	0.42–0.73	0.14	21	2
Methanol	2.6531	−1.0135	0.56011	−0.066634	0.37–0.75	0.23	21	2
Ethanol	1.5508	−0.29351	0.40271	−0.051352	0.38–0.76	0.30	21	2
Propane	1.7962	0.18349	$-0.42295\cdot10^{-2}$	$0.84883\cdot10^{-4}$	0.63–0.88	0.13	21	2
Acetone	2.6501	−1.1140	0.56043	−0.074742	0.38–0.70	0.16	21	5

Table 4 Coefficient values in Eq. (13b) with $c_{pV0} = 10^3$ J/kg·K for specific heat, expressed in J/kg·K, at constant pressure of saturated vapor

	a_0	a_1	a_2	a_3	T_r	ε_{STD}	N	Ref.
R11	0.16116	0.23829	−0.35611	$0.21950\cdot10^{-2}$	0.44–0.85	0.37	21	2
R12	0.27333	0.13204	$-0.89673\cdot10^{-2}$	$0.29244\cdot10^{-3}$	0.55–0.94	0.96	21	2
R13B1	0.26767	0.059363	$-0.15783\cdot10^{-2}$	$0.29526\cdot10^{-4}$	0.63–0.97	1.0	21	2
R21	0.11621	0.28247	−0.046045	$0.32958\cdot10^{-2}$	0.48–0.80	0.057	21	2
R22	0.26461	0.14331	$-0.56889\cdot10^{-2}$	$0.14718\cdot10^{-3}$	0.62–0.95	0.51	21	2
R113	0.082935	0.26105	−0.043745	$0.30186\cdot10^{-2}$	0.49–0.80	0.077	21	2
R114	$0.78600\cdot10^{-2}$	0.40232	−0.079696	$0.58709\cdot10^{-2}$	0.52–0.82	0.20	21	2
R502	0.27978	0.14107	$-0.92002\cdot10^{-2}$	$0.29295\cdot10^{-3}$	0.60–0.93	0.32	21	2
Ammonia	0.58378	0.74239	−0.015578	$0.28015\cdot10^{-3}$	0.49–0.97	0.86	21	2
Water	3.2663	−1.9443	0.79178	−0.080620	0.42–0.73	0.049	21	2
Methanol	−0.070069	1.0951	−0.25883	0.027684	0.43–0.75	1.1	9	3
Ethanol	−0.016678	0.97405	−0.18460	0.012583	0.47–0.79	0.084	9	3
Propane	0.39888	0.51117	−0.046509	$0.19767\cdot10^{-2}$	0.63–0.88	0.17	21	2
Acetone	0.95626	0.82225	−0.15763	0.010823	0.45–0.82	0.17	9	3

Table 5 Coefficient values in Eq. (14a) for specific heat ratio of saturated vapor

	a_0	a_1	a_2	T_r	ε_{STD}	N	Ref.
R11	1.1231	$-0.33009 \cdot 10^{-2}$	$0.46263 \cdot 10^{-2}$	0.44–0.85	0.45	21	2
R12	1.0760	0.032660	$0.11691 \cdot 10^{-2}$	0.55–0.94	0.59	21	2
R13B1	1.0409	0.048277	$0.46424 \cdot 10^{-3}$	0.63–0.97	0.66	21	2
R21	1.2351	−0.052303	0.013081	0.48–0.80	0.26	21	2
R22	1.0604	0.060407	$0.72906 \cdot 10^{-3}$	0.62–0.95	0.59	21	2
R113	1.1250	−0.021838	$0.65285 \cdot 10^{-2}$	0.49–0.80	0.18	21	2
R114	1.1228	−0.025806	$0.58005 \cdot 10^{-2}$	0.52–0.82	0.14	21	2
R502	1.0587	0.037886	$0.68445 \cdot 10^{-3}$	0.60–0.93	0.41	21	2
Ammonia	1.0624	0.11426	$0.24117 \cdot 10^{-3}$	0.47–0.97	1.7	21	2
Water	1.4186	−0.10309	0.030378	0.42–0.73	0.073	21	2
Methanol	1.203	0.0	0.0	0.68–0.69	—	1	6
Ethanol	1.13	0.0	0.0	0.70–0.71	—	1	6
Propane	1.0983	0.027679	$0.16974 \cdot 10^{-2}$	0.63–0.88	0.24	21	2
Acetone	1.07	0.0	0.0	0.50–0.66	—	5	3

Table 6 Coefficient values in Eq. (15) with $k_{L0} = 10^{-1}$ W/m·K for thermal conductivity, expressed in W/m·K, of saturated liquid

	a_0	a_1	a_2	a_3	T_r	ε_{STD}	N	Ref.
R11	1.7073	−1.3028	−0.039064	0.026175	0.44–0.85	0.30	21	2
R12	2.2958	−3.6714	3.3764	−1.6624	0.49–0.99	0.60	21	2
R13B1	1.6989	−1.0821	−0.85347	0.47198	0.41–0.80	0.37	14	2
R21	1.6216	1.0166	−4.5209	2.7157	0.42–0.85	0.62	21	2
R22	3.6921	−8.6065	10.891	−5.6562	0.43–0.95	0.53	21	2
R113	1.4571	−1.2087	−0.10263	0.20656	0.51–0.72	0.033	12	2
R114	1.3955	−0.94967	−0.24560	0.13739	0.42–0.79	0.026	17	2
R502	1.6115	−0.43207	−1.4913	0.75522	0.42–0.85	0.16	17	2
Ammonia	11.719	−9.7598	0.77114	−0.33773	0.54–0.99	0.068	20	2
Water	−9.0825	61.764	−75.636	28.141	0.42–0.73	0.064	21	2
Methanol	2.8709	−1.4261	−0.071216	0.047768	0.42–0.80	0.021	21	2
Ethanol	2.7287	−2.4993	1.6862	−0.95244	0.38–0.76	0.25	21	2
Propane	3.9407	−6.6071	4.5662	−1.2737	0.43–0.98	0.25	21	2
Acetone	4.7919	−13.065	20.851	−12.493	0.45–0.82	1.3	10	3

Table 7 Coefficient values in Eq. (16c) with $k_{V0} = 10^{-2}$ W/m·K for thermal conductivity, expressed in W/m·K, of saturated vapor

	P	a_0	a_{1P}	a_{2P}	a_{3P}	a_{4P}	T_r	ε_{STD}	N	Ref.
R11	2	1.2909	−6.9478	23.058	−26.674	11.061	0.63–1.0	0.56	18	2
R12	2	7.2355	−48.691	129.47	−144.95	59.893	0.62–0.99	2.0	16	2
R13B1	1	2.1017	−6.4848	7.9067	−2.3373	0.0	0.67–0.92	0.24	10	2
R21	2	1.7338	−10.549	34.323	−41.298	18.639	0.60–0.98	0.48	18	2
R22	2	9.7281	−64.653	167.16	−183.82	74.257	0.64–0.98	1.3	14	2
R113	1	−11.760	51.558	−74.069	37.686	0.0	0.56–0.77	0.43	10	7, 8
R114	1	−11.111	42.999	−54.742	25.582	0.0	0.65–0.88	0.12	21	8
R502	2	6.7384	−41.211	102.48	−107.76	41.726	0.67–0.99	1.4	13	2
Ammonia	2	21.079	−139.39	362.57	−399.88	167.34	0.61–0.99	3.4	17	2
Water	1	−2.7452	21.150	−37.710	29.037	0.0	0.42–0.73	0.041	21	2
Methanol	1	0.97095	−3.0978	9.6818	−4.2458	0.0	0.52–0.76	0.29	15	9, 10
Ethanol	1	1.3024	−5.5458	13.577	−5.9771	0.0	0.51–0.80	1.2	19	9, 10
Propane	1	−0.32481	1.9443	0.11954	0.88411	0.0	0.45–0.79	0.21	13	10
Acetone	1	−2.4000	8.5712	−5.3661	1.9445	0.0	0.53–0.79	0.46	6	5

Table 8 Coefficient values in Eq. (17) with $\mu_{L0} = 10^{-3}$ Pa·s for dynamic viscosity, expressed in Pa·s, of saturated liquid

	a_0	a_1	a_2	a_3	T_r	ε_{STD}	N	Ref.
R11	−9.0155	10.413	−4.6555	0.83483	0.46–0.87	0.42	21	2
R12	−31.123	59.866	−41.191	9.7193	0.62–0.99	3.8	16	2
R13B1	−4.1520	1.9207	0.12760	−0.031317	0.55–1.0	0.066	17	2
R21	−8.4086	9.1771	−3.9088	0.66566	0.42–0.85	0.86	21	2
R22	−11.701	15.786	−8.4515	1.7150	0.59–0.95	0.12	15	2
R113	−8.0939	8.9487	−3.8341	0.75202	0.47–0.87	0.87	21	2
R114	−4.9078	2.9086	−0.11372	−0.022966	0.47–0.94	0.77	21	2
R502	−16.151	24.692	−14.185	2.9387	0.53–0.99	2.1	18	2
Ammonia	−29.107	53.785	−36.387	8.4771	0.59–0.99	3.8	18	2
Water	−5.8277	4.6369	−2.0898	0.53748	0.42–0.73	0.35	21	2
Methanol	−6.7047	5.3503	−1.4603	0.24115	0.42–0.80	0.52	21	2
Ethanol	−7.4239	5.7066	−0.96665	0.10107	0.38–0.76	0.38	21	2
Propane	−12.274	15.049	−7.2032	1.2441	0.43–0.98	1.2	21	2
Acetone	−9.8690	12.529	−6.6821	1.3587	0.45–0.82	1.9	10	3

Table 9 Coefficient values in Eq. (18d) with $\mu_{V0} = 10^{-5}$ Pa·s for dynamic viscosity, expressed in Pa·s, of saturated vapor

	P	a_0	a_{1P}	a_{2P}	a_{3P}	a_{4P}	T_r	ε_{STD}	N	Ref.
R11	1	−30.706	125.58	−165.31	73.047	0.0	0.61–1.0	0.019	19	2
R12	2	3.8063	−22.305	62.222	−71.369	30.397	0.62–0.99	0.75	16	2
R13B1	1	−67.132	258.01	−324.43	136.41	0.0	0.67–1.0	0.13	13	2
R21	1	−14.298	58.671	−75.497	33.417	0.0	0.64–1.0	0.018	17	2
R22	2	2.8288	−14.607	40.595	−46.376	19.747	0.64–0.95	0.27	13	2
R113	1	−18.391	75.120	−97.253	42.600	0.0	0.65–0.99	0.020	17	2
R114	1	−14.275	59.485	−77.822	34.771	0.0	0.64–0.98	0.022	16	2
R502	1	−8.7534	37.520	−49.296	22.542	0.0	0.61–0.99	0.20	15	2
Ammonia	2	2.1203	−10.795	32.632	−38.710	16.832	0.59–0.99	0.59	18	2
Water	1	1.1067	−3.3286	8.7661	−4.5611	0.0	0.42–0.73	0.083	21	2
Methanol	2	0.50866	0.51818	4.7323	8.5497	4.8980	0.43–0.96	0.55	21	2, 3
Ethanol	2	0.35405	2.1180	−1.6395	0.25330	0.67535	0.47–0.95	0.64	21	2, 3
Propane	2	0.51503	−1.6466	9.2165	−13.834	7.3872	0.45–0.98	1.9	21	2, 10
Acetone	1	0.20063	0.55343	1.7334	−1.4341	0.0	0.45–0.82	0.65	10	3

Table 10 Coefficient values in Eq. (19) with $h_{L0} = 10^6$ J/kg for specific enthalpy, expressed in J/kg, of saturated liquid

	a_0	a_1	a_2	a_3	T_r	ε_{STD}	N	Ref.
R11	−0.056889	0.54498	−0.28278	0.18489	0.44–0.85	0.030	21	2
R12	−0.089187	0.61065	−0.50433	0.30733	0.55–0.94	0.044	21	2
R13B1	−0.21887	1.1788	−1.3162	0.61951	0.63–0.97	0.12	21	2
R21	0.070803	−0.10627	0.66608	−0.22686	0.48–0.80	0.021	21	2
R22	−0.33186	1.4522	−1.5850	0.80280	0.62–0.95	0.051	21	2
R113	0.070229	0.083386	0.31040	−0.081876	0.49–0.80	0.005	21	2
R114	0.061412	0.0067689	0.36669	−0.078380	0.52–0.82	0.009	21	2
R502	0.084447	−0.15358	0.46286	−0.087992	0.60–0.93	0.020	21	2
Ammonia	−2.5308	4.5749	−4.6194	2.5592	0.49–0.97	1.3	21	2
Water	−1.2903	3.6046	−1.8094	1.2143	0.42–0.73	0.094	21	2
Methanol	0.15816	−2.3401	4.4782	−1.5934	0.53–0.92	7.6	21	2
Ethanol	−0.90975	2.5895	−2.9748	2.1136	0.52–0.99	4.4	15	2
Propane	−1.3916	2.4073	−2.4782	1.3181	0.63–0.88	0.073	21	2
Acetone	−1.1215	0.91975	−0.015483	0.20506	0.41–0.69	0.008	14	11

Table 11 Coefficient values in Eq. (20a) with $h_{V0} = 10^6$ J/kg for specific enthalpy, expressed in J/kg, of saturated vapor

	a_0	a_1	a_2	a_3	T_r	ε_{STD}	N	Ref.
R11	0.30708	−0.060047	0.52488	−0.30691	0.44–0.85	0.006	21	2
R12	0.38849	−0.57904	1.1731	−0.60371	0.55–0.94	0.052	21	2
R13B1	0.51159	−1.1798	1.8152	−0.85276	0.63–0.97	0.096	21	2
R21	0.37733	−0.15955	0.69627	−0.41360	0.48–0.80	0.003	21	2
R22	0.63938	−1.4034	2.3185	−1.1496	0.62–0.95	0.076	21	2
R113	0.28293	−0.023507	0.40174	−0.21553	0.49–0.80	0.002	21	2
R114	0.27336	−0.19064	0.65898	−0.33120	0.52–0.82	0.003	21	2
R502	0.36750	−0.53967	1.1041	−0.56873	0.60–0.93	0.029	21	2
Ammonia	0.93948	−3.8727	7.8621	−4.5753	0.49–0.97	0.80	21	2
Water	2.2629	−0.58528	4.0093	−3.0369	0.42–0.73	0.004	21	2
Methanol	2.4323	−6.9029	11.687	−6.1305	0.53–0.92	0.39	21	2
Ethanol	1.1524	−2.3032	4.7545	−2.5369	0.52–0.91	0.11	21	2
Propane	−0.061741	−0.99980	2.1709	−1.1049	0.63–0.88	0.27	21	2
Acetone	−0.22389	−0.046304	1.0464	−0.55133	0.41–0.69	16.	14	11

Table 12 Coefficient values in Eq. (21) with $\lambda_0 = 10^6$ J/kg for latent heat, expressed in J/kg, of vaporization

	c	n	T_r	ε_{STD}	N	Ref.
R11	0.25886	0.36033	0.44–0.85	0.32	21	2
R12	0.24150	0.37383	0.55–0.94	0.26	21	2
R13B1	0.17511	0.39051	0.63–0.97	0.31	21	2
R21	0.34467	0.37429	0.48–0.80	0.35	21	2
R22	0.34529	0.39064	0.62–0.95	0.37	21	2
R113	0.21562	0.37850	0.49–0.80	0.14	21	2
R114	0.20083	0.36172	0.52–0.82	0.32	21	2
R502	0.25776	0.38858	0.60–0.93	0.52	21	2
Ammonia	1.9620	0.39755	0.49–0.97	0.76	21	2
Water	2.9951	0.32966	0.42–0.73	0.070	21	2
Methanol	1.6044	0.35554	0.53–0.92	1.1	21	2
Ethanol	1.2894	0.38641	0.52–0.99	1.6	15	2
Propane	0.60651	0.36229	0.63–0.88	0.15	21	2
Acetone	0.82813	0.44216	0.45–0.82	2.5	10	3

Table 13 Coefficient values in Eq. (22) with $\sigma_{L0} = 10^{-2}$ N/m for surface tension, expressed in N/m, of saturated liquid

	c	n	T_r	ε_{STD}	N	Ref.
R11	6.2027	1.2482	0.44–0.85	0.071	21	2
R12	5.6794	1.2702	0.55–0.94	0.041	21	2
R13B1	5.2444	1.2668	0.63–0.97	0.084	21	2
R21	6.7318	1.2338	0.53–0.85	0.025	21	2
R22	6.3860	1.2559	0.62–0.95	0.44	21	2
R113	5.5444	1.2404	0.49–0.80	0.071	21	2
R114	5.0997	1.2389	0.64–0.98	0.13	21	2
R502	5.4886	1.2519	0.60–0.93	0.049	21	2
Ammonia	9.5340	1.1556	0.49–0.97	0.038	21	2
Water	12.680	0.90612	0.42–0.73	1.1	21	2
Methanol	4.4995	0.81166	0.42–0.80	0.016	21	2
Ethanol	4.7536	0.87560	0.38–0.76	0.013	21	2
Propane	4.9883	1.1975	0.63–0.88	0.039	21	2
Acetone	6.7966	1.2400	0.45–0.82	3.1	10	3

Table 14 Coefficient values in Eq. (23b) for compressed liquid density expressed in kg/m³

	c_{00}	c_{10}	c_{01}	c_{20}	c_{11}	c_{02}	T_r	p_r	ε_{STD}	N	Ref.
1	1.0423	−0.13613	−0.020261	0.10598	0.047141	$-0.41806\cdot10^{-3}$	0.57–0.77	0.22–2.3	0.054	36	2
2	1.0116	−0.031417	−0.025330	0.017561	0.051881	0.0	0.55–0.77	0.21–0.27	0.003	10	12
3B1	0.98352	0.048527	−0.015452	−0.038697	0.035852	0.0	0.62–0.81	0.22–0.28	0.012	7	12
1	1.0038	−0.012245	−0.0097255	0.0075581	0.026655	0.0	0.47–0.74	0.16–0.22	0.001	13	12
2	3.4628	−5.0973	−0.64553	2.5371	0.85485	−0.022474	0.81–0.98	0.30–2.0	1.1	24	2
13	1.0077	−0.024116	−0.013883	0.014439	0.034997	0.0	0.43–0.77	0.25–0.33	0.006	18	12
14	1.0143	−0.039657	−0.024764	0.022328	0.052184	0.0	0.50–0.80	0.26–0.34	0.007	14	12
02	1.0127	−0.032962	−0.028534	0.017826	0.054900	0.0	0.60–0.77	0.20–0.26	0.002	8	12
mmonia	1.0541	−0.14920	−0.032513	0.095716	0.075450	−0.0025040	0.54–0.84	0.088–1.8	0.11	40	2
ter	1.0227	−0.095902	0.014085	0.10075	−0.0080356	$-0.36502\cdot10^{-3}$	0.42–0.53	0.022–0.91	0.008	36	2

Table 15 Coefficient values in Eq. (24b) for specific heat, expressed in J/kg·K, at constant pressure of compressed liquid

	c_{00}	c_{10}	c_{01}	c_{20}	c_{11}	c_{02}	T_r	p_r	ε_{STD}	N	Ref.
R11	0.76941	0.75724	0.027907	−0.61872	−0.056661	$0.13250\cdot10^{-3}$	0.57–0.64	0.34–1.9	0.021	18	2
R12	0.96125	0.10951	0.067486	−0.069306	−0.13362	0.0	0.55–0.77	0.21–0.27	0.033	10	12
R13B1	0.96344	0.071635	0.14723	−0.018106	−0.25351	0.0	0.62–0.75	0.22–0.28	0.002	6	12
R21	0.97536	0.074092	0.047279	−0.050152	−0.098686	0.0	0.47–0.74	0.16–0.22	0.021	14	12
R22	0.92945	0.20504	0.061585	−0.14200	−0.12338	0.0	0.57–0.74	0.17–0.22	0.026	8	12
R113	0.96079	0.091084	0.087585	−0.043508	−0.14869	0.0	0.43–0.77	0.25–0.33	0.026	14	12
R114	0.95673	0.12504	0.055318	−0.081383	−0.10845	0.0	0.50–0.80	0.26–0.34	0.040	14	12
R502	0.95359	0.11518	0.11255	−0.063159	−0.19402	0.0	0.60–0.77	0.20–0.26	0.046	8	12
Ammonia	0.80148	0.58428	0.072232	−0.41413	−0.15239	0.0062720	0.54–0.84	0.088–1.8	0.32	40	2
Water	0.79647	0.86276	−0.080386	−0.90834	0.13362	0.0015528	0.42–0.53	0.022–0.91	0.081	36	2

Table 16 Coefficient values in Eq. (25b) for thermal conductivity, expressed in W/m·K, of compressed liquid

	c_{00}	c_{10}	c_{01}	c_{20}	c_{11}	c_{02}	T_r	p_r	ε_{STD}	N	Ref.
R11	1.0471	−0.15872	−0.023561	0.12945	0.064517	$-0.35895\cdot10^{-4}$	0.46–0.68	0.11–2.3	0.071	36	2
R12	0.98401	0.088560	−0.020732	−0.10431	0.074338	$-0.72167\cdot10^{-3}$	0.57–0.84	0.24–2.5	0.090	36	2
R13B1	1.1263	−0.18154	−0.094788	−0.0068302	0.16820	0.0014220	0.64–0.94	0.37–2.6	0.79	36	2
R21	1.0	0.0	0.0	0.0	0.0	0.0	—	—	—	8	12
R22	0.58998	1.1774	−0.10254	−0.85870	0.20045	−0.0017652	0.64–0.92	0.40–2.0	0.52	36	2
R113	1.0037	−0.013501	−0.025897	0.011244	0.063102	$0.67036\cdot10^{-4}$	0.53–0.70	0.29–2.7	0.051	36	2
R114	1.0	0.0	0.0	0.0	0.0	0.0	—	—	—	7	12
R502	1.0	0.0	0.0	0.0	0.0	0.0	—	—	—	4	12
Ammonia	1.0281	0.14755	−0.25633	−0.26061	0.41565	−0.013849	0.73–0.89	0.26–1.8	0.37	21	2
Water	1.0580	−0.23964	0.036933	0.24532	−0.035716	$-0.41422\cdot10^{-3}$	0.42–0.56	0.22–0.91	0.034	30	2

Table 17 Coefficient values in Eq. (26b) for dynamic viscosity, expressed in Pa·s, of compressed liquid

	c_{00}	c_{10}	c_{01}	c_{20}	c_{11}	c_{02}	T_r	p_r	ε_{STD}	N	Ref.
R11	1.1546	−0.49618	−0.0019737	0.38963	0.078591	$0.20845\cdot10^{-3}$	0.50–0.73	0.11–1.9	0.13	36	2
R12	0.73872	0.82756	−0.14550	−0.67834	0.30440	−0.0052432	0.67–0.84	0.48–2.5	0.48	36	2
R13B1	2.2229	−1.4927	−0.93588	0.0	1.2585	−0.017886	0.88–0.94	0.75–2.6	0.36	12	2
R21	−0.67723	4.2300	0.0	−2.3659	0.0	0.0	0.60–0.79	0.21–0.22	0.16	5	12
R22	1.0122	0.055597	−0.14035	−0.11838	0.27613	$-0.53001\cdot10^{-3}$	0.59–0.87	0.10–2.0	0.29	36	2
R113	1.1297	−0.38825	−0.0040810	0.28270	0.086093	$0.27720\cdot10^{-3}$	0.56–0.74	0.14–3.0	0.11	36	2
R114	0.12778	2.8542	0.0	−2.1179	0.0	0.0	0.50–0.85	0.33–0.34	0.35	6	12
R502	0.19606	2.5007	−0.46638	−1.8853	0.69601	−0.0020509	0.76–0.96	0.10–2.4	0.97	30	2
Ammonia	2.7819	−3.8729	−0.53337	2.0196	0.77335	−0.0055661	0.78–0.89	0.26–1.8	0.24	15	2
Water	0.76205	1.0136	−0.18283	−1.0717	0.37463	0.0015891	0.42–0.53	0.22–0.91	0.11	24	2

should be employed instead of Eq. (16a). Equations (16a) and (16b) are then unified as

$$k_V/k_{V0} = a_0 + a_{1P}T_r^{1P} + a_{2P}T_r^{2P} + a_{3P}T_r^{3P} + a_{4P}T_r^{4P} \quad (P = 1 \text{ or } 2) \tag{16c}$$

The coefficient values in Eqs. (15) and (16c) are given in Tables 6 and 7, respectively, where $k_{L0} = 10^{-1}$ W/m·K and $k_{V0} = 10^{-2}$ W/m·K.

In evaluating dynamic viscosity of saturated liquid 'μ_L,' recommended is the use of Girifalco's formula[18]

$$\ln(\mu_L/\mu_{L0}) = a_0 + a_1/T_r + a_2/T_r^2 + a_3/T_r^3 \tag{17}$$

where μ_L and μ_{L0} are expressed in Pa·s. With regard to dynamic viscosity of saturated vapor 'μ_V,' the following expression:

$$\mu_V/\mu_{V0} = T_r^{3/2}(a_0 + a_1T_r + a_2T_r^2 + a_3T_r^3) \tag{18a}$$

was first examined. However, recommended are the expressions of positive or even power series expansions

$$\mu_V/\mu_{V0} = a_0 + a_1T_r + a_2T_r^2 + a_3T_r^3 \tag{18b}$$

$$\mu_V/\mu_{V0} = a_0 + a_2T_r^2 + a_4T_r^4 + a_6T_r^6 + a_8T_r^8 \tag{18c}$$

where μ_V and μ_{V0} are expressed in Pa·s. Equations (18b) and (18c) are written in a unified fashion:

$$\mu_V/\mu_{V0} = a_0 + a_{1P}T_r^{1P} + a_{2P}T_r^{2P} + a_{3P}T_r^{3P} + a_{4P}T_r^{4P} \quad (P = 1 \text{ or } 2) \tag{18d}$$

The coefficient values in Eqs. (17) and (18d) are given in Tables 8 and 9, respectively, where $\mu_{L0} = 10^{-3}$ Pa·s and $\mu_{V0} = 10^{-5}$ Pa·s.

Specific enthalpy of saturated liquid and that of saturated vapor, h_L and h_V, have satisfactorily been evaluated by

$$h_L/h_{L0} = a_0 + a_1T_r + a_2T_r^2 + a_3T_r^3 \tag{19}$$

$$h_V/h_{V0} = a_0 + a_1T_r + a_2T_r^2 + a_3T_r^3 \tag{20a}$$

$$h_V/h_{V0} = a_0 + a_1T_r + a_2T_r^2 + a_3T_r^3 + a_4T_r^4 \tag{20b}$$

where h_L, h_{L0}, h_V, and h_{V0} are expressed in J/kg. Since Eq. (20b) does not differ much from Eq. (20a) in accuracy, Eq. (20a) is recommended rather than Eq. (20b). The coefficient values in Eqs. (19) and (20a) are given in Tables 10 and 11, respectively, where $h_{L0} = h_{V0} = 10^6$ J/kg. Latent heat of vaporization can simply be expressed as $\lambda = h_V - h_L$ from the definition. A better estimate of λ has been made by using Thiesen's[19] or Watson's[20] formula

$$\lambda/\lambda_0 = c(1 - T_r)^n \tag{21}$$

where λ and λ_0 are expressed in J/kg. The coefficient and exponent values in Eq. (21) are given in Table 12 where $\lambda_0 = 10^6$ J/kg. Equation (21) is again employed in Eq. (11) to make an estimate of ρ_V.

In expressions concerning surface tension of saturated liquid 'σ_L,' Van der Waals's formula[21] is also acceptable

$$\sigma_L/\sigma_{L0} = c(1 - T_r)^n \tag{22}$$

where σ_L and σ_{L0} are expressed in N/m. The coefficient and exponent values in Eq. (22) are given in Table 13 where $\sigma_{L0} = 10^{-2}$ N/m.

On thermophysical properties of compressed liquids, one knows an expression of the form[22,23]

$$\rho_Q = A_0 + A_1T + A_2T^2 \tag{23a}$$

$$c_{pQ} = A_0 + A_1T + A_2T^2 \tag{24a}$$

$$k_Q = A_0 + A_1T + A_2T^2 \tag{25a}$$

$$1/\mu_Q = A_0 + A_1T + A_2T^2 \tag{26a}$$

where the subscript Q denotes a compressed liquid phase. Equations (23a–26a) were first proposed by Bussolino,[22] who also presented the coefficient values for R21 and E1 (fluorocarbon). However, they do not apply to many cases because pressure dependence was not taken into account. New expressions taking place of Eqs. (23a–26a) are

$$\rho_Q/\rho_L = c_{00} + c_{10}T_r + c_{01}p_r + c_{20}T_r^2 + c_{11}T_rp_r + c_{02}p_r^2 \tag{23b}$$

$$c_{pQ}/c_{pL} = c_{00} + c_{10}T_r + c_{01}p_r + c_{20}T_r^2 + c_{11}T_rp_r + c_{02}p_r^2 \tag{24b}$$

$$k_Q/k_L = c_{00} + c_{10}T_r + c_{01}p_r + c_{20}T_r^2 + c_{11}T_rp_r + c_{02}p_r^2 \tag{25b}$$

$$\mu_Q/\mu_L = c_{00} + c_{10}T_r + c_{01}p_r + c_{20}T_r^2 + c_{11}T_rp_r + c_{02}p_r^2 \tag{26b}$$

where ρ_Q and ρ_L are expressed in kg/m^3, c_{pQ} and c_{pL} in J/kg·K, k_Q and k_L in W/m·K, and μ_Q and μ_L in Pa·s. One here employs Eqs. (10), (12b), (15), and (17) as ρ_L, c_{pL}, k_L, and μ_L in the left-hand sides of Eqs. (23b–26b), respectively. All the coefficient values in Eqs. (23b–26b) are given in Tables 14–17.

Temperature ranges indicating an applicability of the expressions, standard deviations ε_{STD} specifying their accuracies, numbers of data offered for regression analyses, and their origins identified by reference numbers are added in the tables for facilitating reviews of both data and results. Then, as can be clearly seen from the tables, the results are good to such a degree that one may present property data with errors less than 1% in most cases.

Conclusion

Thermophysical properties of 14 saturated fluids and those of 10 compressed liquids are expressible in Eqs. (9b), (10), (12b), (13b), (14a), (15), (16c), (17), (18d), (19), (20a), (21), (22), (23b), (24b), (25b), and (26b) associated with the coefficient values given in Tables 1–17. Hence, they help in design calculations of heat pipes or fluid loops and will also be incorporated into computer codes as a data base.

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