Correlations for some saturated thermodynamic and transport properties of refrigerant R-11

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Abstract

Correlations obtained by linear regression, (least squares), are presented for the saturation temperature $T_s(P)$, saturation pressure $P_s(T)$, vaporization enthalpy $h_{fg}(T)$, vaporization specific volume $v_{fg}(T)$, density of saturated vapour $\rho_g(T)$, saturated liquid dynamic viscosity $\mu_f(T)$, saturated vapour dynamic viscosity $\mu_g(T)$ and the thermal conductivity of saturated liquid $\kappa_f(T)$, covering the complete temperature range given in the data source, (ASHRAE Fundamentals SI). The equations produced are compared graphically with values given in the ASHRAE Fundamentals SI Handbook, and the equations given by ASHRAE whenever possible. Figures show the fitted curves, data points and the resulting errors.

Nomenclature.

A, B, C, D, E	Correlation equation coefficients.	
h	Enthalpy.	kJ/kg
T	Temperature.	K
Tr	Reduced temperature = T/T_c.	
θ	Dimensionless function of temperature, defined in equation 6.	
ϕ	Dimensionless function of temperature, defined in equation 10.	
P	Pressure.	Pa
Pr	Reduced pressure = P/P_c.	
v	Specific volume.	m^3/kg
ρ	Density.	kg/m^3
κ	Thermal conductivity.	W/m-K
μ	Dynamic viscosity.	Pa-s

Subscripts

c	Critical state.
f	Saturated liquid.
fg	Difference between saturated liquid and saturated vapour.
g	Saturated vapour.
s	Saturation.

1. Introduction.

One of the difficulties encountered in the simulation of thermal systems is the reliable modeling of the properties of the working fluid. In some cases precise and complex equations are available over limited ranges. Many of these equations are not convenient for use in simulation programs because the independent variables used are different than those needed in the simulation. There is a need for easy-to-use equations which accurately fit the data over a wide range.

In this paper, correlations for saturation temperature and pressure, enthalpy and specific volume of vaporization, density of saturated vapour, viscosity of saturated liquid and vapour, and thermal conductivity of saturated liquid of R-11 are presented for saturation temperatures between -70 and 198°C. The data used came from ASHRAE Fundamentals [1] and the curve fitting was done using a linear regression analysis, with the least square method as a fidelity criterion [2].

2. Saturation Temperature.

Expressions for the saturation pressure as a function of temperature are available [3], [4], but expressions for saturation temperature as a function of pressure are not readily available.

The equation used for this correlation was of the form:

$$T_s = exp\left[\left\{ \begin{array}{l} A + B \cdot ln(Pr) + C \cdot [ln(Pr)]^2 + \cdots \\ \cdots + D \cdot [ln(Pr)]^3 + E \cdot [ln(Pr)]^4 \end{array} \right\}^{-0.4}\right] \quad (1)$$

where the coefficients are given in Table 1. Figure 1 shows, over the complete range of the source, the data, the fitted curve, and the relative and absolute errors between the fitted curve and the data, relative to the data.

With the exception of the region near the critical point, the fit is very good. See the Table 1 for the percent error range.

3. Saturation Pressure.

Equations exist in the literature which correlate the saturation pressure to the saturation temperature. The proposed correlation reproduces the source data with an error between +0.032 and -0.021%, whereas the ASHRAE equation produces an error between +0.994 and -0.81%, as can be observed in Figure 2.

The equation used for this correlation is:

$$P_s = exp\left[\begin{array}{l} A + B \cdot ln(Tr) + C \cdot \{ln(Tr)\}^2 + \cdots \\ \cdots + D \cdot \{ln(Tr)\}^3 + E \cdot \{ln(Tr)\}^4 \end{array}\right] \quad (2)$$

where the coefficients are given in Table 2. Figure 2 shows the data points, the fitted curve, and the errors associated with the proposed equation and the current ASHRAE equation.

4. Enthalpy of vaporization.

In the ASHRAE publication "Thermodynamic Properties of Refrigerants (1986)" [3], a method to calculate h_{fg}, the difference $h_g - h_f$, is available but it utilizes the Clapeyron equation, which in turn requires the evaluation of h_g, (which alone contains about 20 terms), the derivative dP/dT_s, v_f and v_g.

The equation used here to correlate h_{fg} was:

$$h_{fg} = exp\left[\left(\begin{array}{l} A + B \cdot \{ln(Tr^{-1})\}^{0.1} + C \cdot Tr^{-2} + \cdots \\ \cdots + D \cdot Tr^{-3} + E \cdot Tr^{-4} \end{array}\right)^{0.5}\right] \quad (3)$$

where the coefficients are given in Table 3. Notice that the equation is not defined at the critical point. Figure 3 shows the data points, the fitted curve and the percent error.

5. Specific volume of vaporization.

In the ASHRAE literature the method used is to take the difference between the reciprocals of the saturated vapour density (9 terms for R - 11) [3] and of the saturated liquid density (with 5 terms).

The equation used to correlate the specific volume is:

$$v_{fg} = exp\left[\begin{array}{l} A + B \cdot \{ln(Tr^{-1})\}^{0.15} + C \cdot Tr^{-2} + \cdots \\ \cdots + D \cdot Tr^{-3} + E \cdot Tr^{-4} \end{array}\right] \quad (4)$$

and the coefficients are given in Table 4. Figure 4 shows this correlation. The relative error, as the critical point is approached, becomes very large since v_{fg} approaches zero. The absolute error is very small.

6. Density of saturated vapour.

In the literature there exists a correlation for the density of saturated vapour which contains 9 terms [3].

The equation used here to correlate the density was:

$$\rho_g = exp\left[\begin{array}{l} A + B \cdot \{ln(\theta)\}^{-1.5} + C \cdot \{ln(\theta)\}^{-2} + \cdots \\ \cdots + D \cdot \{ln(\theta)\}^{-3} + E \cdot \{ln(\theta)\}^{-4} \end{array}\right] \quad (5)$$

where θ is defined as:

$$\theta = \frac{1}{1 - Tr} \quad (6)$$

The correlation coefficients are given in Table 5. Figure 5 shows this correlation. In this case, the relative error becomes large as the temperature decreases and the vapour pressure approaches zero.

7. Dynamic viscosity of saturated liquid.

The data for this transport property was taken from ASHRAE [1]. Values for the same property are also given in Touloukian [5]. By comparing the values of both references it was found that they where the same, Touloukian gives an explanation of the origin of the data, and the form of the equation used for its generation to 390 K. Between 390 K and the critical temperature it is stated that "a curve was drawn between the experimental value at 390 K and a calculated value at the critical state". No details are given about the form of this second curve.

In this work an attempt was made to obtain a single equation to reproduce the values given in ASHRAE, without good agreement. Therefore it was decided to use one equation up to the temperature mentioned by Touloukian, and a second one between that point and the critical state. The equations here reported reproduce the source data with errors less than 0.52% over the complete range

The correlation equation for the first part of the curve, valid over the temperature range $170 < T_s < 390$ K, is of the form:

$$\mu_f = exp\left[A + B \cdot Tr^{-1}\right] \quad (7)$$

The second part of the curve, valid for the temperature range $390 < T_s < 470$ K, is correlated by the curve:

$$\mu_f = A + B \cdot \{ln(Tr^{-1})\}^{0.8} + C \cdot (Tr)^{-2} + D \cdot (Tr)^{-3} \quad (8)$$

where the coefficients are given in Table 6: Figure 6 show this results along with the relative error in the current ASHRAE correlation.

8. Dynamic viscosity of saturated vapour.

To correlate this property, one equation was required.

$$\mu_g = exp\left[\left(A + B \cdot \{ln(\phi)\}^{0.05} + C \cdot \{ln(\phi)\}^2\right)^{\frac{1}{1.15}}\right] \cdot 10^{-6}$$

$$.....(9)$$

where the term ϕ is defined as:

$$\phi = \frac{1}{1.000182 - Tr} \qquad (10)$$

and the coefficients are given in Table 7. Figure 7 shows the fitted curve, the data points and the percent errors. Also shown on figure 7 is the curve proposed by ASHRAE with its percent error. It is evident from the graph that the proposed ASHRAE equation is unsuitable for that task.

9. Thermal Conductivity of Saturated Liquid.

By correlating this property, it appeared obvious that the data points corresponding to 156.85 and 166.85°C (430 and 440 K), where incorrect. Therefore they were deleted from the correlation, as can be noticed in Figure 8, near the right end of the curve.

The equation utilized on this correlation was:

$$\kappa_l = exp\left[\begin{array}{l} A + B \cdot ln(1-Tr) + C \cdot \{ln(1-Tr)\}^2 + \cdots \\ \cdots + D \cdot \{ln(1-Tr)\}^3 + E \cdot \{ln(1-Tr)\}^4 \end{array}\right] \cdot 10^{-2}$$

$$.....(11)$$

where the coefficients are given in Table 8. Figure 8 shows the fitted curve, data points and percent errors. The ASHRAE equation relative errors are also shown for comparison.

10. Synopsis.

Simple yet accurate correlations for some saturated thermodynamic and transport properties of refrigerant R-11 have been presented.

Graphic representations of all the fitted curves and source data, as well as incurred error have been shown.

Comparisons against ASHRAE correlations, whenever available, were done.

Similar curve fits can be generated for each refrigerant.

11. References.

[1] 1989 Fundamentals ASHRAE Handbook . pp. 17.3, 17.9

[2] Stoecker, W.F. Design of thermal systems. 3rd. Edit. McGraw-Hill 1989. Chap. 13 pp. 304-330

[3] Stewart,R.B.;Jacobsen,R.T.;Penoncello,S.G. Thermodynamic properties of refrigerants. ASHRAE 1986.

[4] Downing,R.C. Trans. ASHRAE, 80, part 2, pp. 158-169, 1974.

[5] Touloukian,Y.S.; Liley,P.E.; Saxena,S.C. Thermophysical Properties of Matter. Vol. 11 "Viscosity", IFI/Plenum

[6] Thermophysical Properties of Refrigerants. ASHRAE 1976.

Pressure Range:	2643 Pa to 3.9102 MPa
A	1.063259194E-2
B	-6.6783043E-4
C	-1.07995994E-5
D	1.801004211E-6
E	1.482008243E-7
P_c	4.41 MPa
Error:	+0.028% to -0.037%[1]

Table 1   Coefficients for saturation temperature

Temperature Range:	-50 to 190°C
A	15.292303547
B	6.5902286294
C	-1.62405043007
D	3.7727019639
E	-1.761783708E-2
T_c	471.15 K
Error:	+0.032% to -0.021%

Table 2   Coefficients for saturation pressure.

Temperature Range:	-70 to 190°C
A	-13.875226886
B	50.8040440667
C	-8.5805955177
D	5.66096573451
E	-1.1182456824
Error:	+0.064% to -0.127%

Table 3   Coefficients for enthalpy of vaporization.

Temperature Range:	-70 to 190°C
A	-11.0801463813
B	5.420401818782
C	2.05471177521
D	-0.17077480986
E	-1.63205656E-3
Error:	+0.386% to -0.347%

Table 4   Coefficients for specific volume of vaporization

Temperature Range:	-70 to 190°C
A	6.6544353965
B	-12.194472353
C	9.889013458191
D	-3.05991586128
E	0.508806046933
Error:	+0.389% to -0.267%

Table 5   Coefficients for density of saturated vapour

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[1]These values correspond to the maximum percent error between the values predicted by the fitted curves and the data, over the given ranges. For most of the properties here presented these occur at the extremes of the ranges, while over the rest of the range the error is considerably less. Check the corresponding figures to know where the maximum and minimum occur.

Temperature Range:	-103 to 116.5°C	116.5 to 196.5°C
A	-10.594442014222	-5.156092455E-4
B	1.7836371402249	4.396530469E-4
C		1.26930028E-3
D		-7.01487284E-4
Error	+0.112 to -0.117%	+0.519 to -0.438%
Equation:	(7)	(8)

Table 6   Coefficients for dynamic viscosity of saturated liquid

Temperature Range:	-73 to 198°C
A	-10.9493983264
B	13.67572941274
C	-6.661967125E-4
Error:	+0.829% to -0.618%

Table 7   Coefficients for dynamic viscosity of saturated vapour.

Temperature Range:	-73.1 to 186.5°C
A	2.850275117173
B	0.80046260922
C	0.111665073287
D	-1.3802228025E-2
E	-4.2451366451E-3
Error:	+0.052% to -0.04%

Table 8   Coefficients for thermal conductivity of saturated liquid.
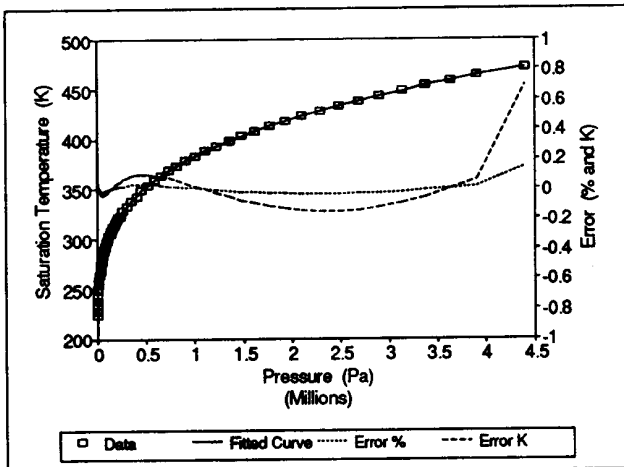
Figure 1   Saturation temperature.
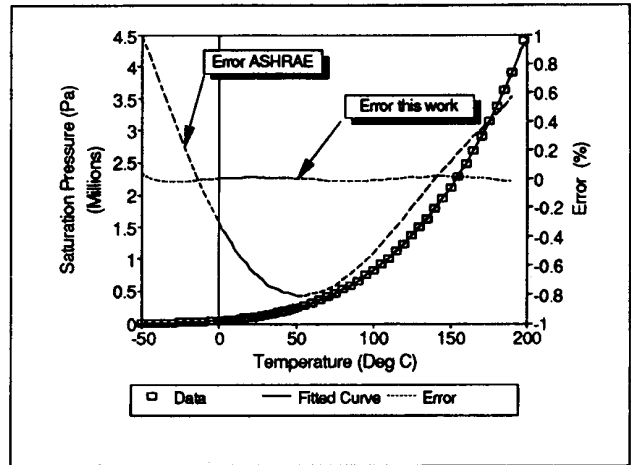
Figure 2 Saturation pressure.
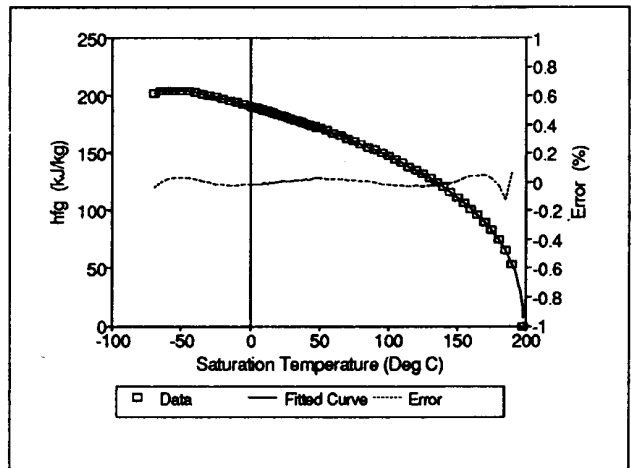
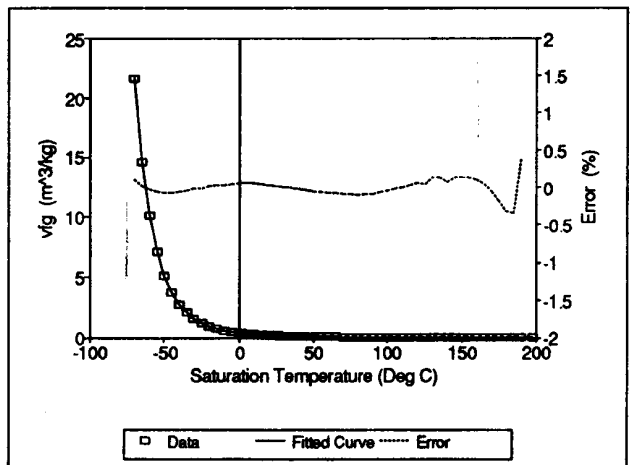Figure 3   Enthalpy of vaporization.

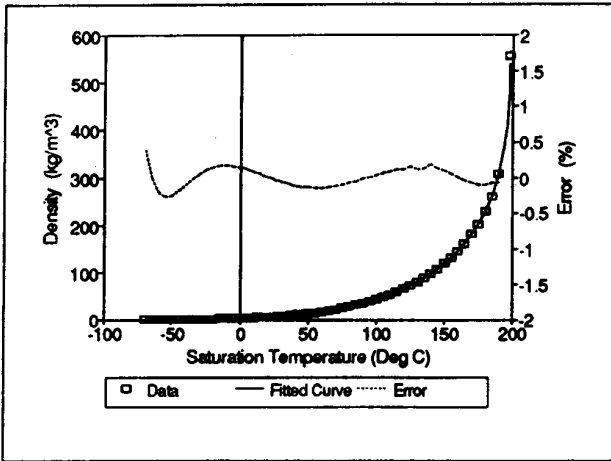Figure 4   Specific volume of vaporization.

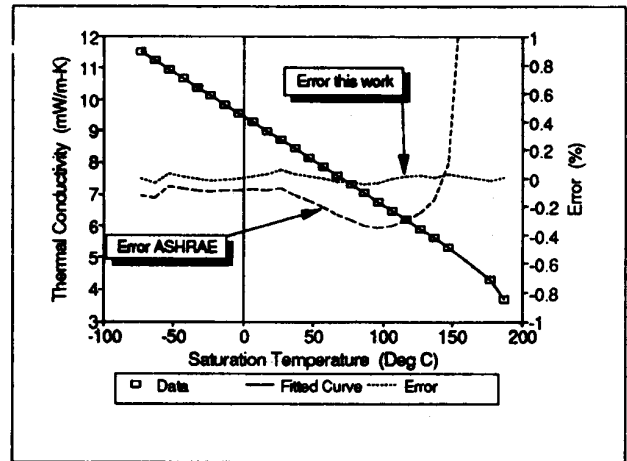Figure 5   Density of saturated vapour.

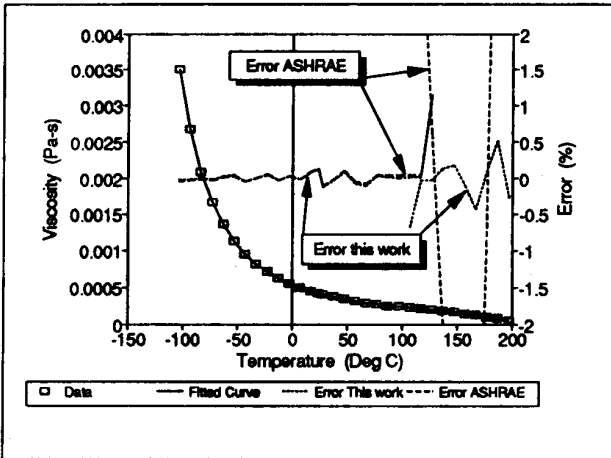Figure 8   Thermal conductivity of saturated liquid.
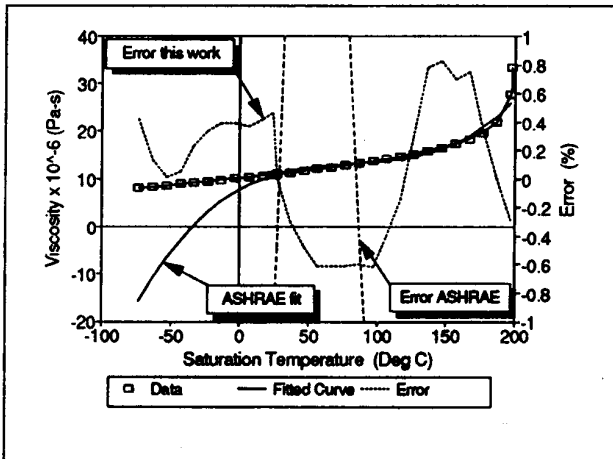

Figure 6   Dynamic viscosity of saturated liquid.

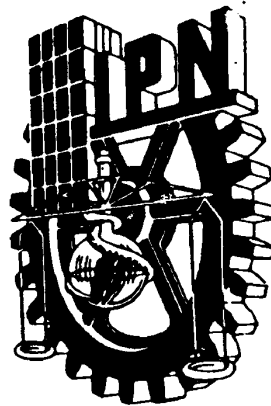Figure 7   Dynamic viscosity of saturated vapour.

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