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SIMPLE FUNCTIONS FOR THE FAST APPROXIMATION OF LIGHT WATER THERMODYNAMIC PROPERTIES

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Thermalhydraulic systems analysis and simulation requires the fast and accurate generation of light water thermodynamic properties. An approach suggested in the past is the use of simple, non-linear functions to give approximations to the properties. Such functions have been developed and are presented here. The range of use is from 0.085 MPa to 21.3 MPa, and from 90 ° C to 450 ° C. In the subcooled and superheated regions the error for enthalpy, entropy and specific volume is usually much less than 1%. This error is based on comparisons to the latest internationally accepted formulation for the thermophysical properties of steam and water. These simple analytic functions provide an alternative to the use of linear interpolation algorithms and complex transcendental equations to generate light water thermodynamic properties. They are well suited to be made into computer subprograms, yet they are simple enough to be used with programmable calculators.

1. Introduction

Light water thermodynamic properties are needed for thermalhydraulic systems analysis. There are several methods of calculating the properties, with varying degrees of accuracy and complexity. For the purposes of system analysis and simulation, it is desirable to have computational functions which are simple enough to use only small amounts of computer memory and time, yet accurate enough to reproduce property values with an error of the order of 0.1%. Simple analytic functions are also desirable as they may easily be differentiated and integrated; continuity of the first derivative of the functions will allow them to be used, for example, in the calculation of the rate form of the equation of state [1] and in algorithms involving the Jacobian of a system matrix.

This paper presents approximate functions which will allow rapid calculation of H_2O thermodynamic properties. The concept is based on existing accurate approximations of H_2O properties at saturation [2]. The functions presented in this paper extend these saturation functions to subcooled and superheated conditions.

2. Overview of existing approximation methods

The reference source of data in this paper is the NBS/NRS Steam Tables [3]. Thermodynamic values listed in the tables are generated from an analytic equation of the form $A = f(\rho, T)$, where ρ is the density and T the absolute temperature. The function A is referred to as the Helmholtz function Equations for all thermodynamic properties are obtained by combinations of appropriate derivatives of A in accordance with the first and second laws of thermodynamics. The formulation in [3] supercedes earlier formulations and was given provisional acceptance by the International Association for the Properties of Steam (IAPS) in 1982. Although invaluable as the ultimate method to generate H_2O thermodynamic properties, routines used to evaluate the equations rely heavily on numerical techniques and contain a large number of constants. The result is complicated algorithms and slow computation time.

An approach which is somewhat simpler and more direct, although no longer as accurate, involves entering part of the actual data tables into computer memory and using linear interpolation algorithms to calculate properties. The disadvantages of this are that large amounts of computer memory is used and that inputting the data is time consuming and error prone.

Development of approximation formulas using the methods of linear and nonlinear regression has been done in the past. While simpler and easier for implementation in computer codes than the two methods described above, there are several undesirable features of this approach. In particular, the best mean square error fitting does not necessarily give the best fit to the data (local deviations can become large). A more fundamental problem lies with fitting smooth functions (thermodynamic properties exhibit smooth behaviour) with polynomials of degree greater than or equal to three, which are oscillatory in nature. Also, in some cases the polynomials are expressed in a nested form which can make analytic differentiation and integration difficult.

3. Approach based on saturation properties and smooth, non-linear functions

Garland and Hoskins [2] have developed approximation formulas for the following thermodynamic properties of light water at saturation, as functions of pressure:
(1) specific volume/density;
(2) specific enthalpy;
(3) saturation temperature;
(4) specific entropy;
(5) specific heat.

Since any given property could not be accurately fitted over the entire pressure range with a single simple expression, the pressure range was partitioned into subranges. The slopes of the curves fits are continuous across the boundaries. The range of use is below one atmosphere to just below the critical point of water (22.09 MPa).

3.1. Subcooled region

Consider an arbitrary thermodynamic property $F = F(P, T)$ where P is the pressure and T is the temperature. The first two terms of a Taylor expansion of F in pressure, about the point at saturation corresponding to the temperature T, are:

$$F(P, T) = F_f(T) + \frac{\partial F}{\partial P}\bigg|_T [P - P_s(T)]. \tag{1}$$

The subscript f on the property F indicates saturation in liquid phase. As noted earlier, saturation formulas [2] are given as functions of pressure rather than temperature. Therefore the temperature T in (1) will have to be changed to its corresponding pressure, using P_s as a function of T, found in Appendix 1. Thus (1) becomes

$$F(P, T) = F_f(P_s(T)) + \frac{\partial F}{\partial P}\bigg|_T [P - P_s(T)] \tag{2}$$

In the compressed liquid region, properties are strong functions of temperature but are only weak functions of pressure (as illustrated in fig. 1, using density as an example). Thus the derivative of the function with respect to pressure will give a slowly varying, almost constant function.

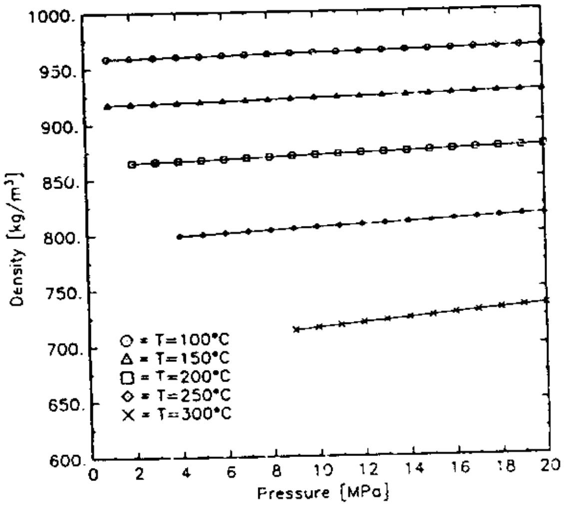

Fig. 1. Liquid density as a function of pressure for a range of temperatures.

Eq. (2) is rearranged to give $(\partial F/\partial P)|_T$:

$$\left.\frac{\partial F}{\partial P}\right|_T = \frac{F - F_{\mathrm{f}}}{P - P_{\mathrm{s}}}. \tag{3}$$

For a given temperature, this derivative is calculated over the entire pressure range (from about 0.07 to 20 MPa) and then averaged. This is done for temperatures from 90 °C to 350 °C. The resulting averages are fitted with a simple, non-linear function of temperature.

The principal advantage of using eq. (1) is that it gives continuous values for the property as saturation is approached. This makes it ideal for use in systems designed to operate at or close to saturation conditions.

3.2. Superheated region

The approach described above for subcooled thermodynamic properties is inadequate for the superheated region, where properties may vary strongly with both pressure and temperature. Consider again an arbitrary thermodynamic property $F = F(P, T)$. The first two terms of a Taylor expansion of F in temperature, about the point at saturation corresponding to the pressure P, are:

$$F(P, T) = F_{\mathrm{g}}(P) + \left.\frac{\partial F}{\partial T}\right|_P (T - T_{\mathrm{s}}). \tag{4}$$

The subscript g on the property F indicate saturation in the gas phase. Since the derivative $(\partial F/\partial T)|_P$ will be a sensitive function of both pressure and temperature, let

$$R(P, T) = \left.\frac{\partial F}{\partial T}\right|_P. \tag{5}$$

By rearranging (4), $R(P, T)$ is evaluated and plotted using a spreadsheet program on a microcomputer. The issue, then, is to fit $R(P, T)$. The reason for using eq. (4) is that the first term, which has been fitted very accurately, is the dominant term and errors in the fit of R will not be as crucial as they would if the property was fitted directly, without reference to the value of saturation.

3.3. Fitting of $R(P, T)$

$R(P, T)$ is a function of two variables and thus is difficult to fit. The procedure used is to plot R as a function of pressure, for several constant temperatures, and observe the set of curves generated. A number of common and special curves were examined from the literature [4,5] and a set was chosen which closely resembles those of $R(P, T)$. For some of the properties it is only necessary to either add or multiply a simple function of pressure of temperature to $R(P, T)$ in order to force it to resemble a family of curves. In all cases, the functions chosen to generate $R(P, t)$ are simple and nonlinear in nature.

3.4. Advantages of this formulation

The formulation presented above allows the user great flexibility in implementing the approximation functions. If the pressure and temperature range required are known beforehand, only the relevant saturation functions need be entered. This enables memory use and computational time to be kept to a minimum. The functions can therefore be used on programmable calculators, personal computers, mainframes, for "back of the envelope" calculations, in spreadsheets and in large simulation codes.

Nonlinear functional approximation has been utilized before (for example, see ref. [6]). The present formulation is unique, however, in the use of saturation values as the dominant terms in the approximation expressions. As mentioned previously, this makes the functions useful for systems designed to operate at or near saturation. However, the use of saturation values as a 'basis' does not limit the functions to near-saturation conditions. The fits are quite accurate even in the far superheated and subcooled regions.

The slopes are easily determined and are accurate enough (see Section 6) for use in iterative searches.

4. Correlations of subcooled light water

Thermodynamic properties

The approximation functions for the following thermodynamic properties in subcooled conditions are presented here:

(1) density,
(2) specific enthalpy,
(3) specific entropy,
(4) specific heat.

The form of the function is

$$F(P, T) = F_f(P_s(T)) + R(T)(P - P_s). \tag{6}$$

The equations for P_s as a function of T are listed in Appendix I. The procedure then, for finding a property F given a pressure P and temperature T, is

(1) find P_s from temperature T (Appendix I),
(2) find $F_f(P_s)$ using saturation equations listed,
(3) evaluate equation to get $F(P, T)$.

For each property, the range of use is specified, along with a brief summary of the error involved in using the approximation functions. Plots of the property and of the error are also included. The errors are percentage errors, defined the usual way as:

$$\text{Percentage error} = \frac{F_{\text{approx.}} - F_{\text{ref}}}{F_{\text{ref}}} \times 100,$$

where

F_{approx} is the value of the property calculated using the approximation equations.

F_{ref} is the value of the property calculated using the formulation of ref. [3].

4.1. Density, liquid phase

The functions listed below, when used in conjunction with the formulas for P_s as a function of T listed in Appendix I, give approximations to the density of light water in liquid phase, $\rho[\mathrm{m}^3/\mathrm{kg}]$. They are valid in the range from 91.79–357.03° C and from saturation to 21.5 MPa. Below 12 MPa the error is not worse than 0.1%. Above 12 MPa the error can be as high as 0.5%.

$$\rho(P, T) = \rho_f(P_s(T)) + \left[\frac{170}{375 - T} - 0.2\right](P - P_s).$$

where

$$\rho_f = \left[1.2746977 \times 10^{-4} P_s^{0.4644339} + 0.001000\right]^{-1} \quad \text{for } 0.075\ \text{MPa} \le P_s \le 1.000\ \text{MPa};$$

$$\rho_f = \left[1.0476071 \times 10^{-4} P_s^{0.5651090} + 0.001022\right]^{-1} \quad \text{for } 1.000\ \text{MPa} < P_s \le 3.880\ \text{MPa};$$

$$\rho_f = \left[3.2836717 \times 10^{-5} P_s + 1.12174735 \times 10^{-3}\right]^{-1} \quad \text{for } 3.880\ \text{MPa} < P_s \le 8.840\ \text{MPa};$$

$$\rho_f = \left[3.3551046 \times 10^{-4}\, \mathrm{e}^{(5.8403566 \times 10^{-2} P_s)} + 0.00085\right]^{-1} \quad \text{for } 8.840\text{MPa} < P_s \le 14.463\ \text{MPa};$$

$$\rho_f = \left[3.1014626 \times 10^{-8} P_s^{3.284754} + 0.001430\right]^{-1} \quad \text{for } 14.463\ \text{MPa} < P_s < 18.052\ \text{MPa};$$

$$\rho_f = \left[1.5490787 \times 10^{-11} P_s^{5.7205} + 0.001605\right]^{-1} \quad \text{for } 18.052\ \text{MPa} \le P_s < 20.204\ \text{MPa};$$

$$\rho_f = \left[4.1035988 \times 10^{-24} P_s^{15.03329} + 0.00189\right]^{-1} \quad \text{for } 20.204\ \text{MPa} \le P_s \le 21.500\ \text{MPa}.$$

4.2. Specific enthalpy, liquid phase

The functions listed below, when used in conjunction with the formulas for P_s as a function of T listed in Appendix I, give approximations to the specific enthalpy of light water in liquid phase, h[kJ/kg]. They are valid in the range from 91.79–357.03° C and from saturation to 21.7 MPa. The error is below 0.15%.

$$h(P, T) = h_f(P_s(T)) + \left[1.4 - \frac{169}{369 - T}\right](P - P_s).$$

where

$$h_s = 912.1779 P_s^{0.2061637} - 150.0 \quad \text{for } 0.075\ \text{MPa} < P_s < 0.942\ \text{MPa};$$

$$h_s = 638.0621 P_s^{0.2963192} + 125.0 \quad \text{for } 0.942\ \text{MPa} \le P_s < 4.020\ \text{MPa};$$

$$h_s = 373.7665 P_s^{0.4235532} + 415.0 \quad \text{for } 4.020\ \text{MPa} \le P_s < 9.964\ \text{MPa};$$

$$h_s = 75.38673 P_s^{0.8282384} + 900.0 \quad \text{for } 9.964\ \text{MPa} \le P_s < 16.673\ \text{MPa};$$

$$h_s = 0.1150827 P_s^{2.711412} + 1440.0 \quad \text{for } 16.673\ \text{MPa} \le P_s < 20.396\ \text{MPa};$$

$$h_s = 9.1417257 \times 10^{-14} P_s^{11.47287} + 1752.0 \quad \text{for } 20.396\ \text{MPa} \le P_s \le 21.700\ \text{MPa}.$$

4.3. Specific entropy, liquid phase

The functions listed below when used in conjunction with the formulas for P_s as a function of T listed in Appendix I, give approximations to the specific entropy of light water in liquid phase, s[kJ/kg.k]. They are valid in the range from 89.96–357.03° C and from saturation to 21.25 MPa. The error is below 0.15%.

$$s(P, T) = s_f(P_s(T)) + \left[0.0004 - \frac{0.325}{370 - T}\right](P - P_s),$$

where

$s_f = 3.340244 P_s^{0.125474} - 1.20$ for 0.065 MPa $\le P_s <$ 1.666 MPa;
$s_f = 1.748203 P_s^{0.2275611} + 0.40$ for 1.666 MPa $\le P_s <$ 8.825 MPa;
$s_f = 0.2549238 P_s^{0.6381866} + 2.25$ for 8.825 MPa $\le P_s <$ 16.66 MPa;
$s_f = 4.3632383 \times 10^{-5}(P_s - 0.40)^{2.153273} + 3.50$ for 16.660 MPa $\le P_s <$ 21.250 MPa.

4.4. Specific heat, liquid phase

The functions listed below, when used in conjunction with the formulas for P_s as a function of T listed in Appendix I, give approximations to the constant pressure specific heat of light water in liquid phase, C_p[kJ/kg K]. They are valid in the range from 89.96–357.03° C and from saturation to 20.3 MPa. Below 12 MPa the error is not greater than 0.5%. Above 12 MPa the error can be as high as 2%.

$$C_p(P, T) = C_{pf}(P_s(T)) + \left[0.0018 - \frac{76}{(364 - T)^{1.8}}\right](P - P_s),$$

where

$C_{pf} = 0.247763 P_s^{0.5704026} + 4.150$ for 0.030 MPa $< P_s \le$ 0.671 MPa;
$C_{pf} = 0.1795305 P_s^{0.8957323} + 4.223$ for 0.671 MPa $< P_s \le$ 2.606 MPa;
$C_{pf} = 0.09359843 P_s^{1.239114} + 4.340$ for 2.606 MPa $< P_s \le$ 6.489 MPa;
$C_{pf} = 0.01068888 P_s^{2.11376} + 4.740$ for 6.489 MPa $< P_s \le$ 11.009 MPa;
$C_{pf} = 1.333058 \times 10^{-4} P_s^{3.707294} + 5.480$ for 11.009 MPa $< P_s \le$ 14.946 MPa;
$C_{pf} = 6.635658 \times 10^{-3}(P_s - 10.0)^{3.223323} + 7.350$ for 14.946 MPa $< P_s \le$ 18.079 MPa;
$C_{pf} = 4.6844786 \times 10^{-6}\, e^{0.7396875 P_s} + 10.020$ for 18.079 MPa $< P_s \le$ ~~20.300~~ 21.5 MPa.

5. Correlations of superheated light water thermodynamic properties

Approximation functions for the following thermodynamic properties in superheated conditions are presented here:

(1) specific volume,
(2) specific enthalpy,
(3) specific entropy,
(4) specific heat.

The form for the functions is

$$F(P,T)=F_g(P)+R(P,T)\cdot(T-T_s). \tag{7}$$

The equations for T_s as a function of P are listed in Appendix II.

5.1. *Specific volume, vapour phase*

The functions listed below give approximations to the specific volume of light water in vapour phase. v[m^3/kg]. They are valid in the range from 0.085 MPa–21.5 MPa, and from saturation to 450°C. The error is less than 1%.

$$v(P,T)=v_g(P)+\left[\frac{0.000466}{P}-\frac{[0.12/(T+100)-0.00106]\,P^{0.1}}{\sqrt{1.96\times10^{-8}(T+8)^4-P^2}}\right](T-T_s),$$

where

$v_g=[5.126076P^{0.9475862}+0.012]^{-1}$ for 0.085 MPa $< P <$ 1.112 MPa:

$v_g=[4.630832P^{1.038819}+0.520]^{-1}$ for 1.112 MPa $\le P <$ 3.932 MPa:

$v_g=[2.868721P^{1.252148}+3.800]^{-1}$ for 3.932 MPa $\le P <$ 8.996 MPa:

$v_g=[0.5497653P^{1.831182}+18.111]^{-1}$ for 8.996 MPa $\le P <$ 14.628 MPa;

$v_g=[8.5791582\times10^{-3}P^{3.176484}+50.000]^{-1}$ for 14.628 MPa $\le P \le$ 18.210 MPa:

$v_g=[3.5587113\times10^{-6}P^{5.660939}+88.000]^{-1}$ for 18.210 MPa $< P \le$ 20.253 MPa;

$v_g=[3.558734\times10^{-16}P^{13.03774}+138.000]^{-1}$ for 20.253 MPa $< P \le$ 21.500 MPa.

5.2. *Specific enthalpy, vapour phase*

The functions listed below give approximations to the specific enthalpy of light water in vapour phase. h[kJ/kg]. They are valid in the range from 0.075 MPa–21.55 MPa and from saturation to 450°C. The error is less than 0.8%.

$$h(P,T)=h_g(P)+\left[\frac{4.5P}{\sqrt{7.4529\times10^{-6}T^3-P^2}}+0.28\,e^{-0.008(T-162)}-\frac{100}{T}-2.225\right](T-T_s).$$

where

$h_g=-4.0381938\times10^{-6}(3.0-P)^{15.72364}+2750.0$ for 0.075 MPa $< p \le$ 0.348 MPa:

$h_g=-0.5767304\,e^{-1.66153(P-3.2)}+2800.0$ for 0.348 MPa $< P \le$ 1.248 MPa:

$h_g=-7.835986(\overset{P-3.001}{\cancel{3.001-P}})^{2.0}\overset{-}{+}2.934312\overset{(P-3.001)}{(\cancel{3.001-P})}+2803.71$ for 1.248 MPa $< P <$ 2.955 MPa:

$h_g=-1.347244(P-2.999)^{2.0}-2.326913(P-2.999)+2803.35$ for 2.955 MPa $\le P \le$ 6.522 MPa:

$h_g=-0.9219176(P-9.00)^{2.0}-16.38835(P-9.00)+2742.03$ for 6.522 MPa $< P <$ 16.497 MPa:

$h_g=-3.532177(P-8.00)^{2.0}+29.81305(P-8.00)+2\,565.00$ for 16.497 MPa $\le p <$ 20.193 MPa:

$h_g=-22.92521(P-18.0)^{2.0}+44.23671(P-18.0)+2415.01$ for 20.193 MPa $\le P \le$ 21.550 MPa.

5.3. Specific entropy, vapour phase

The functions listed below give approximations to the specific entropy of light water in vapour phase s[kJ/kg K]. They are valid in the range from 0.070 MPa–21.5 MPa, and from saturation to 450 °C. The error is less than 0.75%.

$$s(P,T)=s_g(P)+\left[\frac{0.004P^{1.2}}{\sqrt{3.025\times10^{-11}(T+46)^5-P^2}}+\frac{0.00006}{\sqrt{P}}-4.125\times10^{-6}T+0.0053\right](T-T_s),$$

where

$s_g=6.58681-0.335924\log P$ for $0.025\ \text{MPa}\le \overset{P}{\cancel{P}}\le 1.480\ \text{MPa}$;

$s_g=7.80-1.227644P^{0.2481072}$ for $1.480\ \text{MPa}<P\le 8.050\ \text{MPa}$;

$s_g=6.30-0.084638514P^{0.9082161}$ for $8.050\ \text{MPa}<P\le 15.640\ \text{MPa}$;

$s_g=5.50-3.6897161\times10^{-3}(P-7.80)^{2.012466}$ for $15.640\ \text{MPa}<P\le 20.000\ \text{MPa}$;

$s_g=5.00-0.042830642(P-18.7)^{1.779526}$ for $20.000\ \text{MPa}<P\le 21.500\ \text{MPa}$.

5.4. Specific heat, vapour phase

The functions listed below give approximations to the specific heat of light water in a vapour phase, C_p[kJ/kg K]. They are valid in the range from 0.070 MPa–20.4 MPa, and from saturation to 400 °C. ~~The error is less than 5%.~~ When the pressure is above 0.070 MPa, the error is less than 5%; when the pressure is less than 0.070 MPa, the error is slightly higher than

$$C_p(P,T)=C_{pg}(P)-\left[\frac{0.011P}{\left[0.00014(T+8)^2-P\right]^{1.5}}+1.5\times10^{-8}(655-T)^{2.1}\right]P(T-T_s),$$

where

$C_{pg}=0.6471635(P-0.006)^{0.6400369}+1.90$ for $0.050\ \text{MPa}\le P<0.599\ \text{MPa}$;

$C_{pg}=0.5560633P^{0.8197355}+2.00$ for $0.599\ \text{MPa}\le P<2.391\ \text{MPa}$;

$C_{pg}=0.3187082P^{1.110271}+2.30$ for $2.391\ \text{MPa}\le P<5.661\ \text{MPa}$;

$C_{pg}=0.064275995P^{1.765196}+3.12$ for $5.661\ \text{MPa}\le P<9.458\ \text{MPa}$;

$C_{pg}=3.8011048\times10^{-3}P^{2.816897}+4.40$ for $9.458\ \text{MPa}\le P\le 12.900\ \text{MPa}$;

$C_{pg}=0.1876175\ \mathrm{e}^{0.2466925P}+5.00$ for $12.900\ \text{MPa}<P\le 16.309\ \text{MPa}$;

$C_{pg}=7.620756\ \mathrm{e}^{0.4117289P}+9.20$ for $16.309\ \text{MPa}<P<18.743\ \text{MPa}$;

$C_{pg}=6.5162612\ \mathrm{e}^{0.7562118P}+17.10$ for $18.743\ \text{MPa}\le P\le 20.400\ \text{MPa}$.

6. Partial derivatives of approximation functions

A useful advantage of the above approximation functions is the ease with which analytic expressions for the partial derivatives (P and T are the independent variables) may be obtained. Recalling the expression for an arbitrary thermodynamic property $F = F(P, T)$ in the subcooled region,

$$F(P, T) = F_f(P_s(T)) + R(T) \cdot [P - P_s(T)], \tag{8}$$

the partial derivatives are

$$\left(\frac{\partial F}{\partial P}\right)_T = R(T), \tag{9}$$

$$\left(\frac{\partial F}{\partial T}\right)_P = \frac{\mathrm{d}R}{\mathrm{d}T}[P - P_s(T)] + \frac{\mathrm{d}P_s}{\mathrm{d}T}\left[\frac{\mathrm{d}F_f}{\mathrm{d}P} - R(T)\right]. \tag{10}$$

In the superheat region, the thermodynamic property

$$F(P, T) = F_g(P) + R(P, T)[T - T_s(P)] \tag{11}$$

has partial derivatives

$$\left(\frac{\partial F}{\partial P}\right)_T \overset{=}{\cancel{\;\;}} \frac{\mathrm{d}F_g}{\mathrm{d}P} + \left(\frac{\partial R}{\partial P}\right)_T [T - T_s(P)] - R(P, T)\frac{\mathrm{d}T_s}{\mathrm{d}P}, \tag{12}$$

$$\left(\frac{\partial F}{\partial T}\right)_P = R(P, T) + \left(\frac{\partial R}{\partial \underset{P}{\cancel{T}}}\right)_T [T - T_s(P)]. \tag{13}$$

Appendix III lists the partial derivatives for specific volume, enthalpy and entropy.

Figs. 2a and 2b show the average error obtained from using the derivatives $(\partial F/\partial P)_T$ and $\partial F/\partial T)_P$, where F is density, enthalpy or entropy in the subcooled region. For each abscissa value of P, the ordinate

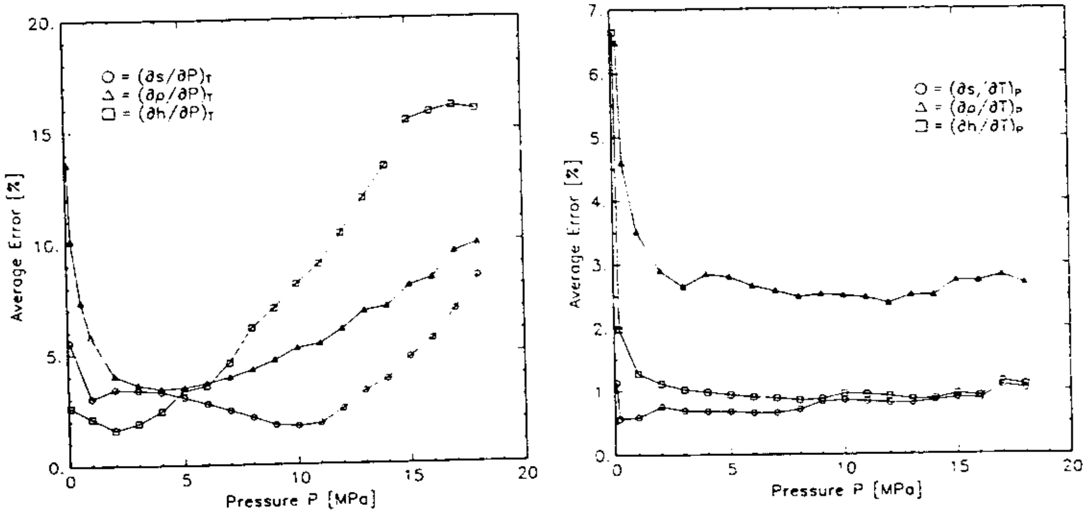

Fig. 2a. Average errors for derivatives of subcooled thermodynamic properties. 2b. Average errors for derivatives of subcooled thermodynamic properties.

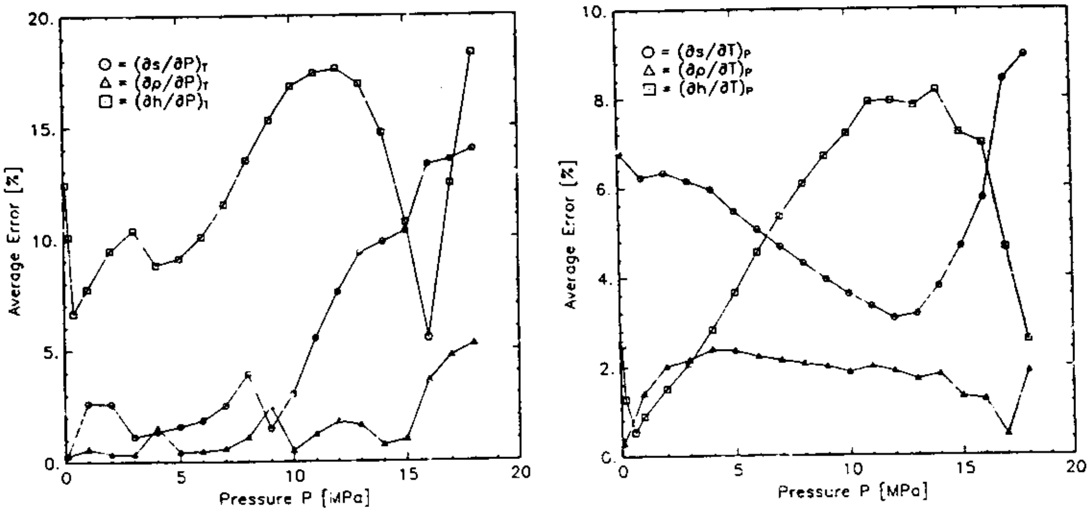

Fig. 3a. Average errors for derivatives of superheated thermodynamic properties. 3b. Average errors for derivatives of superheated thermodynamic properties.

value is obtained by averaging the percentage error over the temperature range (from saturation to 90 ° C) for that pressure.

The derivative $(\partial h/\partial P)_T$ is a strong function of temperature and for pressures above 5 MPa becomes zero for certain temperatures. Close to the zero points the relative error is high. The high errors are not physically meaningful, however, and are not included in the average error calculations.

Figs. 3a and 3b display the average errors obtained from using the derivatives $(\partial F/\partial P)_T$ and $(\partial F/\partial T)_P$ in the superheated vapour phase. We note that the average errors for $(\partial h/\partial P)_T$ are anomalously high. The reason for this is as follows: Enthalpy, in the superheat phase, is not a strong function of pressure. Fig. 4 illustrates this. The derivative $(\partial h/\partial P)_T$ is plotted over the pressure range for a sample temperature

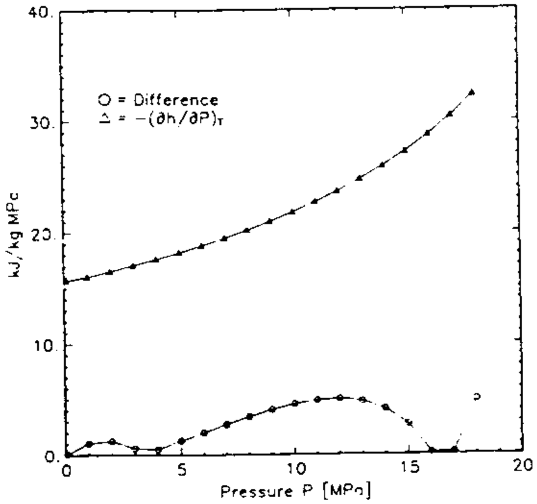

Fig. 4. Slope $(\partial h/\partial p)_T$ as function of pressure for $T = 400$ ° C, and difference between slope and approximation.

(400 °C), and one can see that a typical value (20 kJ/kg MPa) is very small in comparison to enthalpy itself (~ 2600 kJ/kg). Even though the absolute error in the enthalpy is small, minor derivatives in the local shape of the fitted enthalpy function dominate the calculated slope because the nominal value of the slope is near zero. Had the slope been steeper, the local function shape would have not contributed significantly to the overall error in the slope.

The problem is particularly severe at low pressures where the saturation enthalpy varies strongly with pressure while the superheated enthalpy does not. For a given pressure and temperature (P, T), applying a pressure adjustment factor

$$P \rightarrow P + 0.13\left[P_s(T) - P\right]$$

helps remedy the problem to some extent. The adjustment amounts to using the derivative value at a pressure isothermally closer to saturation; it can be applied to the entire pressure range even though it is mean for low pressures.

The above discussion has illustrated one disadvantage of the approximation method presented in this paper. In the far superheat region traditional methods of approximation may be more appropriate if accurate values of the slope are of great importance. We point out, however, that continuity of the derivatives as saturation is approached will in some numerical work outweigh the importance of having highly accurate approximations to the derivative values. This may especially be true in the case of superheated enthalpy, where the derivative $(\partial h/\partial P)_T$ is very small in comparison to $h(P, T)$.

While analytic expressions for the derivatives are relatively easy to obtain, the following thermodynamic relationships may be used to further reduce the amount of computation required:

$$\left(\frac{\partial h}{\partial T}\right)_P = C_\mathrm{p}, \tag{14}$$

$$\left(\frac{\partial s}{\partial T}\right)_P = \frac{C_\mathrm{p}}{(T + 273.15)}, \tag{15}$$

$$\left(\frac{\partial s}{\partial P}\right)_T = v^2\left(\frac{\partial \rho}{\partial T}\right)_P 1000. \tag{16}$$

Equations (14) and (15) will also give more accurate values for the derivatives (accurate to the tolerance of constant pressure specific heat) when compared to the full expressions from the approximation function. However, when the derivatives are required in a searching algorithm (finding pressure for a given entropy and temperature, for example) the full expressions may yield more consistant results.

Finally, one should note that the approximation functions and derivatives presented in this paper may be used to approximate some commonly used thermodynamic and transport properties, such as the speed of sound, ω:

$$\omega = \sqrt{\left|\frac{C_\mathrm{p}}{(T + 273.15)}\,\frac{1}{A}\right|}, \tag{17}$$

where

$$A = \left(\frac{\partial \rho}{\partial P}\right)_T 10^{-6}\frac{C_\mathrm{p}}{(T + 273.15)} - \frac{1}{\rho^2}\left(\frac{\partial \rho}{\partial T}\right)_P^2 10^{-3}.$$

7. Summary

The functions presented in this paper allow rapid calculation of the thermodynamic properties of light water. They cover a pressure range from below one atmosphere to 21.30 MPa, and temperature range from 90 °C to 450 °C. They are accurate enough for the purpose of thermalhydraulic systems analysis. It should be noted that internal energy, u, can be calculated using the correlations for specific volume and specific enthalpy via the equation $u = h - Pv$.

These fits, coded as FORTRAN functions on an IBM-PC $5\frac{1}{4}''$ floppy diskette, can be obtained by corresponding with Dr. Wm.J. Garland, Department of Engineering Physics, McMaster University, 1280 Main St. W., Hamilton, Ontario, L8S 4M1.

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Appendix I. Saturation pressure as a function of temperature

The correlations given below are for saturation pressure, P_s[MPa]. The temperature range for which they may be used is 89.965 °C to 373.253 °C, with an error of not worse than 0.02%.

$$P_s = \left[\frac{(T+57.0)}{236.2315} \right]^{5.602972} \quad \text{for } 89.965\,^\circ\text{C} \le T < 139.781\,^\circ\text{C},$$

$$P_s = \left[\frac{(T+28.0)}{207.9248} \right]^{4.778504} \quad \text{for } 139.781\,^\circ\text{C} \le T < 203.662\,^\circ\text{C},$$

$$P_s = \left[\frac{(T+5.0)}{185.0779} \right]^{4.304376} \quad \text{for } 203.662\,^\circ\text{C} \le T < 299.407\,^\circ\text{C},$$

$$P_s = \left[\frac{(T+16.0)}{195.1819} \right]^{4.460843} \quad \text{for } 299.407\,^\circ\text{C} < T < 355.636\,^\circ\text{C},$$

$$P_s = \left[\frac{(T+50.0)}{227.2963} \right]^{4.960785} \quad \text{for } 355.563\,^\circ\text{C} \le T \le 373.253\,^\circ\text{C}.$$

See Garland et al
(1992) for updates

Appendix II. Saturation temperature as a function of pressure

The correlations given below are for saturation temperature, T_s[°C]. The pressure range for which may be used is 0.070 MPa to 21.85 MPa with an error of not worse then 0.02%.

$$T_s = 236.2315 P^{0.1784767} - 57.0 \quad \text{for } 0.070\text{ MPa} \le P < 0.359\text{ MPa},$$

$$T_s = 207.9248 P^{0.2092705} - 28.0 \quad \text{for } 0.359\text{ MPa} \le P \le 1.676\text{ MPa},$$

$$T_s = 185.0779 P^{0.2323217} - 5.0 \quad \text{for } 1.676\text{ MPa} < P \le 8.511\text{ MPa},$$

$$T_s = 195.1819 P^{0.2241729} - 16.00 \quad \text{for } 8.511\text{ MPa} < P < 17.690\text{ MPa},$$

$$T_s = 227.2963 P^{0.201581} - 50.0 \quad \text{for } 17.690\text{ MPa} \le P \le 21.850\text{ MPa}.$$

Appendix III. Partial derivatives

The partial derivatives of specific volume are:

$$\left(\frac{\partial v}{\partial P}\right)_T = \left[\frac{170}{375-T} - 0.2\right]^{-1} \quad \text{(subcooled)},$$

$$\left(\frac{\partial v}{\partial P}\right)_T = \frac{\mathrm{d}v_g}{\mathrm{d}P} - \left[\frac{0.000466}{P} \frac{-(0.12/(T+100)-0.00106)P^{0.1}}{\sqrt{1.96\times10^{-8}(T+8)^4-P^2}}\right]\frac{\mathrm{d}T_s}{\mathrm{d}P}$$

$$+\Bigg[\frac{-0.000466}{P^2} - \frac{(0.12/(T+100)-0.00106)0.1P^{-0.9}}{\sqrt{1.96\times10^{-8}(T+8)^4-P^2}} -$$

$$-\frac{(0.12/(T+100)-0.00106)P^{1.1}}{\left(1.96\times10^{-8}(T+8)^4-P^2\right)^{1.5}}\Bigg](T-T_s(P)) \quad \text{(superheat)},$$

$$\left(\frac{\partial v}{\partial T}\right)_P = \left\{\left[\frac{170}{(375-T)^2}\right][P-P_s(T)] + \frac{\mathrm{d}P_s}{\mathrm{d}T}\left[\frac{\mathrm{d}v_f}{\mathrm{d}P} + 0.2 - \frac{170}{375-T}\right]\right\}^{-1} \quad \text{(subcooled)},$$

$$\left(\frac{\partial v}{\partial T}\right)_F = \frac{0.000466}{P} \frac{-(0.12/(T+100)-0.00106)P^{0.1}}{\sqrt{1.96\times10^{-8}(T+8)^4-P^2}}$$

$$+[T-T_s(P)]\Bigg[\frac{[0.12/(T+100)]^{2}P^{0.1}}{\sqrt{1.96\times10^{-8}(T+8)^4-P^2}}$$

$$+\frac{(0.12/(T+100)-0.00106)P^{0.1}3.92\times10^{-8}(T+8)^3}{\left(1.96\times10^{-8}(T+8)^4-P^2\right)^{1.5}}\Bigg] \quad \text{(superheat)}.$$

The partial derivatives for specific enthalpy are:

$$\left(\frac{\partial h}{\partial P}\right)_T = 1.4 - \frac{169}{369-T} \quad \text{(subcooled)},$$

$$\left(\frac{\partial h}{\partial P}\right)_T = \frac{\mathrm{d}h_g}{\mathrm{d}P} - \left[\frac{4.5P}{\sqrt{7.4529\times10^{-6}T^3-P^2}} + 0.28\,\mathrm{e}^{-0.008(T-162)} - \frac{100}{T} + 2.225\right]\frac{\mathrm{d}T_s}{\mathrm{d}P}$$

$$+[T-T_s(P)]\left[\frac{4.5}{\sqrt{7.4529\times10^{-6}T^3-P^2}} + \frac{4.5P^2}{(7.4529\times10^{-6}T^3-P^2)^{1.5}}\right] \quad \text{(superheat)}.$$

$$\left(\frac{\partial h}{\partial T}\right)_P = \left[\frac{-169}{(369-T)^2}\right][P-P_s(T)] + \frac{\mathrm{d}P_s}{\mathrm{d}T}\left[\frac{\mathrm{d}h_f}{\mathrm{d}P} + \frac{169}{369-T} - 1.4\right] \quad \text{(subcooled)}.$$

$$\left(\frac{\partial h}{\partial T}\right)_P = \frac{4.5P}{\sqrt{7.4529\times10^{-6}T^3-P^2}} + 0.28\,\mathrm{e}^{-0.008(T-1752)} -- \frac{100}{T} + 2.225$$

$$+\left[\frac{-5.03071\times10^{-5}PT^2}{(7.4529\times10^{-6}T^3-P^2)^{1.5}} - 0.00224\,\mathrm{e}^{-0.008(T-162)} + \frac{100}{T^2}\right][T-T_s(P)] \quad \text{(superheat)}.$$

The partial derivatives for specific entropy are

$$\left(\frac{\partial s}{\partial P}\right)_T = 0.0004 - \frac{0.325}{370 - T} \quad \text{(subcooled)},$$

$$\left(\frac{\partial s}{\partial P}\right)_T = \frac{\mathrm{d}s_g}{\mathrm{d}P} - \left[\frac{0.004P^{1.2}}{\sqrt{3.025\times10^{-11}(T+46)^5 - P^2}} + \frac{0.00005}{\sqrt{P}} - 4.125\times10^{-6} \ast T + 0.005\overset{3}{\cancel{2}}\right]\frac{\mathrm{d}T_s}{\mathrm{d}P}$$

$$+\left[T - T_s(P)\right]\left[\frac{0.0048P^{0.2}}{\sqrt{3.025\times10^{-11}(T+46)^5 - P^2}}\right.$$

$$\left. + \frac{0.004P^{2.1}}{\left[3.025\times10^{-11}(T+46)^5 - P^2\right]^{1.5}} - \frac{2.5\times10^{-5}}{P^{1.5}}\right] \quad \text{(superheat)},$$

$$\left(\frac{\partial s}{\partial T}\right)_P = \left[\frac{-0.325}{(370 - T)^2}\right]\left[P - P_s(T)\right] + \frac{\mathrm{d}P_s}{\mathrm{d}T}\left[\frac{\mathrm{d}s_f}{\mathrm{d}\underset{P}{\cancel{T}}} + \frac{0.325}{370 - T} - 0.0004\right] \quad \text{(subcooled)},$$

$$\left(\frac{\partial s}{\partial T}\right)_P = \frac{0.004P^{1.2}}{\sqrt{3.025\times10^{-11}(T+46)^5 - P^2}} + \frac{5.0\times10^{-5}}{\sqrt{P}} - 4.125\times10^{-6}T$$

$$+0.0053 + \left[T - T_s(P)\right]\left[\frac{-0.3025\times10^{-13}P^{1.2}(T+46)^4}{\left[3.025\times10^{-11}(T+46)^5 - P^2\right]^{1.5}} - 4.125\times10^{-6}\right] \quad \text{(superheat)}.$$

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Extensions to the approximation functions for the fast calculation of saturated water properties

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The knowledge of accurate physical properties of water is fundamental for the analysis of thermalhydraulic systems and the design of a broad range of equipment in many diverse fields. Whilst formulations do exist for the accurate calculation of these properties they often prove too slow for many engineering and technological applications. The rapid generation of these properties without relinquishing accuracy has been the purpose of previous work. This paper presents extensions to the range of validity of the functions developed in the earlier work.

The low pressure range for the saturation properties has been extended downward from approximately 0.08 MPa and 90°C. Also some modifications were made to allow all functions to have a consistent upper pressure limit of 21.5 MPa. This now gives a useful range from 0.002 MPa to 21.5 MPa and 18°C to 450°C.

The accuracy of these functions has been evaluated by calculating the deviation from the latest internationally accepted formulations for the thermophysical properties of steam and water. Namely the International Association for the Properties of Water formulation for the Thermodynamic Properties of Ordinary Water Substance for Scientific and General Use, 1984.

The deviations from these formulations are very small usually much less than 0.2 percent in the valid pressure and temperature range. Only near the critical pressure do these deviations exceed this but in no case does the deviation exceed 0.6 percent.

1. Introduction

The simple approximations for the rapid calculation of the thermophysical properties of water recently proposed by Garland & Hoskins (1988) [1] for the saturated region and Garland & Hand (1989) [2] for the subcooled and superheated regions are gaining approval from a variety of users both for their speed and simplicity. These formulations are especially convenient when the rate form of the equation of state is used in simulation codes (Garland & Sollychin, 1987) [3]. They are valid for pressures from about 0.08 to 21.5 MPa and for temperatures from 90 to 450°C.

However, in many engineering applications, such as flow in turbines, condensers, low pressure regenerative heat exchangers, turbine vapour separators, reheaters etc., pressures below 0.08 MPa are quite common. New approximations have been developed using the same methodology for pressures down to 0.002 MPa for saturated conditions for those functions which are simple functions of pressure.

In addition a simple approximation for saturated pressure as a function of temperature down to 18°C has also been developed.

With these extensions the formulations now cover the range 0.002 to 21.5 MPa and 18 to 450°C. In all cases the efficacy of these functions is evaluated by calculating the deviation from the formulations accepted by the International Association for the Properties of Water in 1984 (IAPS-84) [4].

It should be noted that the IAPS-84 accepted formulations supersede all earlier previously approved

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formulations, including the Keenan, Keyes, Hill and Moore; the Pollak; and the 1968 IFC Formulation for Scientific, Technical, and Engineering use.

2. Existing methods

The IAPS approved formulations for the evaluation of water properties for scientific use is clearly the best available in terms of accuracy and they have been extensively tested against experimental data. They are also international in scope because the IAPS has been actively involved in testing and validating the formulations and in critically reviewing them. However they do result in cumbersome computer codes which are slow in operation.

In order to improve computation times a variety of simpler and more direct techniques have been tried in the past. The use of precalculated tables of property data, for example, can result in increases in speed but the use of linear interpolation algorithms often negate this. Also accuracy is sacrificed and a large amount of computer memory is required.

3. The correlation of the properties

The approach taken to correlating the thermodynamic properties consists of two parts. First the deviations of the saturated properties from the reference data are minimized by dividing the pressure range into several regions.

Second functions for each pressure range are then fitted to the data using the method of least squares. This requires minimising the sum of the squares of the deviations from the reference data as follows.

If we represent a set of data points by the relationship $y=f(x)$ then the deviations from the reference data are:

$$D_i=f(x_i)-y_i,$$

and the sum of the squares of the deviations.

$$S=\sum_{i=1}^{n} D_i^2=\sum_{i=1}^{n}\left[f(x_i)-y_i\right]^2$$

The function $y=f(x)$ is a linear function while the thermodynamic properties are usually best represented by non-linear functions of forms similar to $y=ax^b$ or $y=ae^{bx}$. Reference [1] shows how the reference data was altered to transform these functions into linear forms. In addition all the functions are required to exhibit a continuous derivative across the entire range of pressure.

4. Extensions to the ranges

New approximations were developed according to the methodology outlined above for pressure down to 0.002 MPa for the following properties: saturated temperature, density of saturated liquid, specific volume of saturated vapour, specific enthalpy and specific entropy of saturated liquid and saturated vapour.

No new techniques were employed to extend the ranges of the original functions although some minor modifications were made to them in order to maintain continuity with the new ones and to keep deviations as low as possible. The extended low pressure ranges were tested against the IAPS-84 approved formulations by the co-authors Garland & Wilson with computer code from the NBS/NRC [6] and against the IAPS-84 approved formulation [4] coded at the National Research Institute for Machine Design, Czechoslovakia by co-authors Bartak, Cizek, Stastny and Zentrich.

5. Modifications

In addition to the extensions the upper pressure ranges of each of the saturated functions has been examined and in the interests of consistency each one terminated at 21.5 MPa. Appendix I contains the complete set of functions in tabular form and the ranges for which they are valid. Various users have brought to the author's attention a number of minor errors in the formulations. These are identified and corrected in Appendix I.

6. Evaluation of accuracy

Figure 1 shows the percentage deviation from the reference data for Saturation Pressure as a function of temperature for the saturation temperature range 18 to 373°C. It may be seen that the absolute deviation generally is less than 0.05 percent. Only below about 90°C does the deviation exceed this by a significant amount. Even so the maximum deviation of this function only reaches its maximum of −0.1836 percent at a temperature of 47.5°C.

Figure 2 shows the percentage deviation from the reference data for Saturation Temperature as a func-

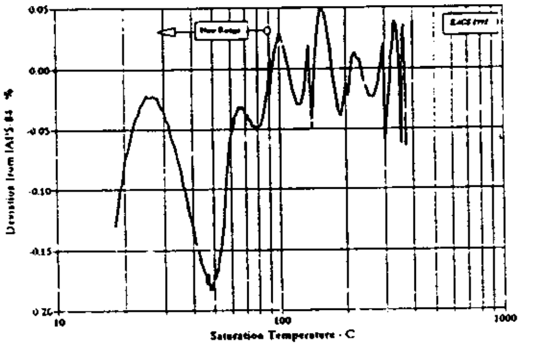

Fig. 1. Deviation in the saturation pressure for the temperature range 18–373°C.

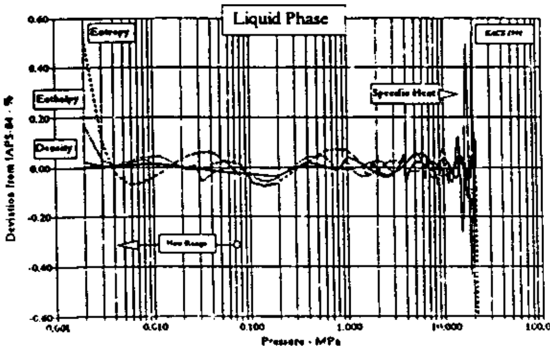

Fig. 3. Deviation of saturation properties for the pressure range 0.002–21.5 MPa.

tion of pressure for the saturation pressure range 0.002 to 21.5 MPa Here the absolute deviation is well below 0.02 percent for most of the range and only exceeds 0.02 percent when the pressure is less than 0.07 MPa. It reaches its maximum of 0.1314 percent at the minimum low pressure of 0.002 MPa.

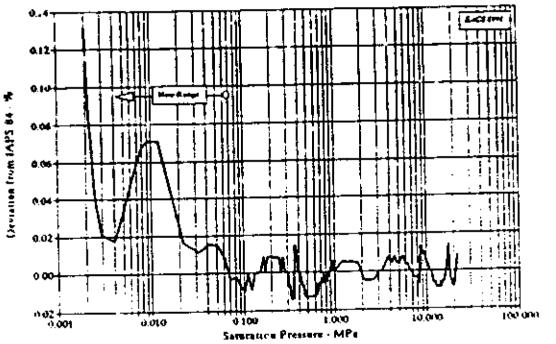

Fig. 2. Deviation in saturation temperature for the pressure range 0.002–21.5 MPa.

Figures 3 and 4 show the percentage deviation of the saturation properties for the liquid phase and vapour phase respectively.

For the liquid phase over most of the pressure range the absolute deviations are well below 0.10 percent. The maximum deviations are seen at the extreme low end and at the extreme high end of the pressure range. Only at 21.20 MPa and 0.002 MPa for specific entropy do the absolute deviations exceed 0.20 percent. Nonetheless the deviations of 0.56 percent at 0.002 MPa and 0.5921 percent at 21.40 MPa still provide useful estimates for entropy.

For the vapour phase the absolute deviations are all less than 0.20 percent when the saturation pressure is less than 21.0 MPa. Only the density and volume functions show absolute deviations greater than 0.20

Table 1
Statistics for the percentage deviations from IAPS-84

Property	Standard deviation	Root mean square	Maximum
Liquid density ρ_l	0.04	0.04	0.18 @ 20.202 MPa
Vapour density ρ_g	0.10	0.10	0.36 @ 21.202 MPa
Liquid enthalpy h_l	0.03	0.03	0.17 @ 0.002 MPa
Vapor enthalpy h_g	0.03	0.03	0.11 @ 16.4 MPa
Liquid entropy s_l	0.08	0.08	−0.59 @ 21.4 MPa
Vapour entropy s_g	0.03	0.03	0.08 @ 1.4 MPa
Liquid specific heat C_{p_l}	0.14	0.14	−0.46 @ 20.6 MPa
Vapour specific heat C_{p_g}	0.12	0.12	−0.60 @ 21.5 MPa
Saturation pressure P_{sat}	0.05	0.07	−0.18 @ 47.5°C
Saturation temperature T_{sat}	0.02	0.02	0.13 @ 0.002 MPa

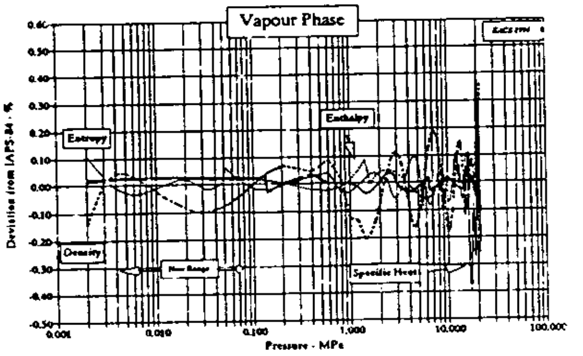

Fig. 4. Deviation of saturation properties for the pressure range 0.002–21.5 MPa.

percent when the pressure is greater than about 21.20 MPa. This is due to increasing the useful pressure range to 21.5 MPa. The result is increases in maximum deviation to −0.3624.

7. Discussion

A complete listing of all the modified funtions is contained in Table 1 along with the maximum percentage deviation from the reference data.

Based on the foregoing results it is clear that the absolute deviations of the functions become notably larger than average only for the pressure dependant functions at the extremes of the pressure ranges. Even so inspection of the maximum deviations from IAPS-84 in table 1 reveals that these are not excessive and that useful estimates can still be obtained.

In the case of the temperature dependant saturation pressure function the estimates are remain remarkably accurate over the entire 18 to 373°C range despite the maximum deviation of −0.1836 percent.

8. Conclusion

The simple formulations presented here permit rapid calculation of the thermodynamic properties of water with an accuracies that are more than adequate for a broad variety of engineering and technological tasks.

Table A-1
Saturation pressure as a function of temperature

Saturation pressure P_s (MPa) for 18 to 373°C

$$P_s(T)=\left[\frac{(T+a)}{b}\right]^c$$

Temperature range (°C)	a	b	c
17.511 [1] ≤ T < 56.275	99.2	270.1210	7.4063650
56.275 [1] ≤ T < 90.880	78.2	254.6831	6.4058216
90.880 [2] ≤ T < 139.781	57.0	236.2315	5.6029720
139.781 ≤ T < 203.662	28.0	207.9248	4.7785040
203.662 ≤ T ≤ 299.407	5.0	185.0779	4.3043750
299.407 [3] < T < 355.636	16.0	195.1819	4.4608430
355.563 ≤ T ≤ [4] 373.000	50.0	227.2963	4.9607850

[1] New functions
[2] Modified pressure range
[3] Corrected from < in ref. [2]
[4] Modified from 373.253 in ref. [2]

The saturation properties now cover the pressure range 0.002 to 21.5 MPa and a temperature range 18 to 373°C. Work on extending the subcooled and superheated properties to cover the same ranges is continuing.

The formulations have been coded in FORTRAN and are available on a 5-1/4 inch MS-DOS diskette by contacting Dr. Wm. J. Garland, Department of Engineering Physics, McMaster University, 1280 Main St. West, Hamilton, Ontario, L8S 4M1.

Table A-2
Saturation temperature as a function of pressure

Saturation temperature T_s (°C) for 0.002 to 21.5 MPa
$T_s(P) = aP^b + c$

Pressure range (MPa)	a	b	c
[1] 0.00200 ≤ P < 0.01672	270.1210	0.135019	−99.2
[1] 0.01672 ≤ P < 0.07250	254.6831	0.156108	−78.2
[2] 0.07250 ≤ P ≤ [3] 0.35900	236.2315	0.1784767	−57.0
[3] 0.35900 < P ≤ 1.67600	207.9248	0.2092705	−28.0
1.67600 < P ≤ 8.51100	185.0779	0.2323217	−5.0
8.51100 < P < 17.69000	195.1819	0.2241729	−16.0
17.69000 ≤ P ≤ 21.500	227.2963	0.2015810	−50.0

[1] New function
[2] Modified pressure range
[3] Corrected from ≤ in refs. [1] and [2].

Table A-3
Specific density of the liquid phase at saturation

Specific density, ρ_1 (kg/m^3) for 0.002 to 21.5 MPa and T_s to 450°C where:
$\rho_l(P) = [aP_s^b + c]^{-1}$

Pressure range (MPa)	a	b	c
0.002 [1] $\le P < 0.01468$	1.9118×10^{-4}	0.546472	0.0009947
0.01468 [1] $\le P < 0.275$	1.380934×10^{-4}	0.388715	0.000987
0.275 [2] $\le P \le 1.000$	1.2746977×10^{-4}	0.4644339	0.00100000000
$1.000 < P \le 3.880$	1.0476071×10^{-4}	0.5651090	0.00102200000
$3.880 < P \le 8.840$	3.2836717×10^{-5}	1.0000000	0.00112174735
$8.840 < P \le 14.463$	See Note 1	See Note 1	See Note 1
$14.463 < P < 18.052$	3.1014626×10^{-8}	3.2847540	0.00143000000
$18.052 \le P < 20.204$	$1.5490787 \times 10^{-11}$	5.7205000	0.00160500000
$20.204 \le P \le 21.500$	$4.1035988 \times 10^{-24}$	15.0332900	0.0018900000

[1] New function

[2] Modified pressure range.

Note 1: $\rho_l(P) = [3.3551046 \times 10^{-4}\, e^{5.8403566 \times 10^{-2} P_s} + 0.00085]^{-1}$

Table A-4
Specific enthalpy for the liquid phase at saturation

Specific enthalpy, h_1 (kJ/kg) for 0.002 to 21.5 MPa and T_s to 450°C where:
$h_l(P) = aP_s^b + c$

Pressure range (MPa)	a	b	c
[1] $0.0020 \le P < 0.0173$	1128.7770	0.1351960	−413.72
[1] $0.0173 \le P < 0.1028$	1050.7085	0.1617970	−306.50
[2] 0.1028 [3] $\le P \le 0.9420$	912.1779	0.2061637	−150.00
$0.9420 \le P < 4.0200$	638.0621	0.2963192	125.00
$4.0200 \le P < 9.964$	373.7665	0.4235532	415.00
$9.964 \le P < 16.673$	75.38673	0.8282384	900.00
$16.673 \le P < 20.396$	0.1150827	2.711412	1440.00
$20.396 \le P$ [4] ≤ 21.500	$9.1417257 \times 10^{-14}$	11.47287	1752.00

[1] New function

[2] Modified pressure range

[3] Corrected from < in ref. [2]

[4] Corrected from 21.7 in ref. [2]

Table A-5
Specific entropy of the liquid phase at saturation

Specific entropy, S_1 (kJ/kg K) for 0.002 to 21.5 MPa and T_s to 450°C where:
$s_l(P) = a(P_s + b)^c + d$

Pressure range (MPa)	a	b	c	d
[1] $0.0020 \le P < 0.0812$	4.5397665	0.0	0.0829772	−2.449
[2] $0.0812 \le P < 1.6660$	3.340244	0.0	0.125474	−1.200
$1.6660 \le P < 8.8250$	1.748203	0.0	0.2275611	0.400
$8.8250 \le P < 16.6600$	0.2549238	0.0	0.6381866	2.250
[2] $16.6600 \le P$ [3] ≤ 21.5000	4.3632383×10^{-5}	−0.04	3.153273	3.500

[1] New function

[2] Modified pressure range

[3] Corrected from < in ref. [3].

Table A-6
Specific heat of the liquid phase at saturation

Specific heat, C_{p_1} (kJ/kg K) for 0.03 to 21.5 MPa and T_s to 450°C where:
$C_{p_1}(P) = a(P_s - b)^c + d$

Pressure range (MPa)	a	b	c	d
$0.002 \le P \le 0.030$	18.10909	0.01240	2.0	4.1779
$0.030 < P < 0.671$	0.247763	0.0	0.5704026	4.150
$0.671 \le P < 2.606$	0.1795305	0.0	0.8967323	4.223
$2.606 \le P < 6.489$	0.09359843	0.0	1.239114	4.340
$6.489 \le P < 11.009$	0.01068888	0.0	2.113760	4.740
$11.009 \le P < 14.946$	1.333058×10^{-4}	0.0	3.707294	5.480
$14.946 \le P < 18.079$	6.635658×10^{-3}	−10.0	3.223323	7.350
$18.079 \le P \le 21.30$	See Note 1	See Note 1	See Note 1	See Note 1
$20.3 < P \le 21.00$	See Note 2	See Note 2	See Note 2	See Note 2
$21.0 < P \le 21.50$	See Note 3	See Note 3	See Note 3	See Note 3

Note 1: $C_{p_1}(P) = 4.6844786 \times 10^{-6}\, e^{0.7396875 P_s} + 10.020$
Note 2: $C_{p_1}(P) = 2.3434679 \times 10^{-14} \exp 1.64194406 P + 18.770$
Note 3: $C_{p_1}(P) = 38485636.1747 - 7311152.45563 P + 520882.9814112 P^2 \underset{-}{\cancel{+}} 16494.9064728 P^3 + 195.8985209777 P^4$.
(Note: this correction is not in the code version 1.03)

Table A-7
Specific volume for the vapour phase at saturation

Specific volume, v_g (m^3/kg) for 0.002 to 21.5 MPa and T_s to 450°C where:
$v_g(P) = \{aP^b + c\}^{-1}$

Pressure range (MPa)	a	b	c
0.002 [1] $\le P < 0.2139$	5.0981616	0.936226	−0.00025
0.2139 [2] $\le$ [3] $P < 1.1120$	5.126076	0.9475862	0.012
$1.112 \le P < 3.932$	4.630832	1.038819	0.520
$3.932 \le P < 8.996$	2.868721	1.252148	3.800
$8.996 \le P < 14.628$	0.5497653	1.831182	18.111
$14.628 \le P \le 18.210$	8.5791582×10^{-3}	3.176484	50.000
$18.210 < P \le 20.253$	3.5587113×10^{-6}	5.660939	88.000
$20.253 < P \le 21.5$	3.558734×10^{-16}	13.03774	138.000

[1] New function
[2] Modified pressure range
[3] Corrected from < in ref. [2]

Table A-8
Specific enthalpy of the vapour phase at saturation

Specific enthalpy, h_g (kJ/kg) for 0.002 to 21.5 MPa and T_s to 450°C where:
$h_g(P) = a(P+b)^2 + c(P+b) + d$

Pressure range (MPa)	a	b	c	d
0.002 [1] $\le P < 0.1379$	See Note 1	See Note 1	See Note 1	See Note 1
0.1379 [2] $\le$ [3] $P < 0.348$	See Note 2	See Note 2	See Note 2	See Note 2
$0.348 < P \le 1.248$	See Note 3	See Note 3	See Note 3	See Note 3
$1.248 < P < 2.955$	-7.835986	-3.001	-2.934312	2803.71
$2.955 \le P \le 6.522$	-1.347244	-2.999	-2.326913	2803.35
$6.522 < P < 16.497$	-0.9219176	-9.0	-16.38835	2742.03
$16.497 \le P < 40.193$	-3.532177	-8.0	29.81305	2565.00
$20.193 \le P \le 21.5$ [4]	-22.92521	-18.0	44.23671	2415.01

[1] New function
[2] Modified pressure range
[3] Corrected from < in ref. [2]
[4] Modified from 21.550 in ref. [2]
Note 1: $h_g(P) = 529.44008\,P^{0.108652} + 2263.5$
Note 2: $h_g(P) = -4.0381938 \times 10^{-6}(3.0 - P)^{15.72364} + 2750.0$
Note 3: $h_g(P) = -0.5767304\,e^{-1.66153(P-3.2)} + 2800.0$

Table A-9
Specific entropy of the vapour phase at saturation

Specific entropy, s_g (kJ/kg K) for 0.002 to 21.5 MPa and T_s to 450°C where:
$s_g(P) = a(P+b)^c + d$

Pressure range (MPa)	a	b	c	d
0.002 [1] $\le P < 0.0916$	16.644669	0	-0.0192733	-10.039
0.0916 [2] $\le P <$ [3] 1.480	See Note 1	See Note 1	See Note 1	See Note 1
$1.480 < P \le 8.050$	1.227544	0	0.2481072	7.80
$8.050 < P \le 15.640$	-0.084638514	0	0.9082161	6.30
$15.640 < P \le 20.00$	$-3.6897161 \times 10^{-3}$	-7.80	2.012466	5.50
$20.000 \le$ [4] $P \le 21.50$	-0.042830642	-18.7	1.779526	5.0

[1] New function
[2] Modified pressure range
[3] Corrected from ≤ in ref. [2]
[4] Corrected from < in ref. [2].
Note 1: $s_g(P) = 6.58681 - 0.335924 \log P$

Table A-10
Specific heat for the vapour phase at saturation

Specific heat, vapour phase, C_{p_g} (kJ/kg K) for 0.05 to 20.4 MPa and T_s to 450°C where:
$C_{p_g}(P) = a(P+b)^c + d$

Pressure range (MPa)	a	b	c	d
$0.002 \leq P < 0.050$	See Note 1	See Note 1	See Note 1	See Note 1
$0.050 < P \leq {}^{3}0.599$	0.6471635	−0.006	0.6400569	1.90
$0.599 < {}^{2}P \leq {}^{3}2.391$	0.5560633	0	0.8197355	2.00
$2.391 < {}^{2}P \leq {}^{3}5.661$	0.3187082	0	1.110271	2.30
$5.661 < {}^{2}P \leq {}^{3}9.458$	0.064275995	0	1.766106	3.12
$9.458 < {}^{2}P \leq 12.900$	3.8011048×10^{-3}	0	2.816897	4.40
$12.900 < P \leq 16.309$	See Note 2	See Note 2	See Note 2	See Note 2
$16.309 < P \leq {}^{3}18.743$	See Note 3	See Note 3	See Note 3	See Note 3
$18.743 < {}^{2}P \leq 20.400$	See Note 4	See Note 4	See Note 4	See Note 4
$20.400 < P \leq 21.500$	See Note 5	See Note 5	See Note 5	See Note 5

[1] Corrected from 0.070 in ref. [2]

[2] Corrected from $\leq$ in ref. [2]

[3] Corrected from $<$ in ref. [2]

Note 1: $C_{p_1} = 1.8720218136 + 5.19125176488P - 136.166377842P^2 + 2364.55677P^3 - 16088$

Note 2: $C_{p_g}(P) = 0.1876175\,e^{0.2466925P} - 5.00$

Note 3: $C_{p_g}(P) = 7.6207560\,e^{0.4117289P} - 9.20$

Note 4: $C_{p_g}(P) = 6.5162612\,e^{0.7562118P} - 17.10$

Note 5: $C_{p_1}(P) = 12698166.64211 - 2459483.262925P + 178557.414749P^2 - 5768.512569602P^3 + 69.854295639476P^4$

Acknowledgements

The authors wish to thank the Faculty of Engineering, McMaster University, and the Natural Sciences and Engineering Research Council of Canada for partially funding this project.

References

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[3] W.J. Garland and R. Sollychin, Rate form of the equation of state for thermalhydraulic systems: Numerical considerations, Engineering Computations 4, No. 4 (December 1987).

[4] V.V. Sytchev and H.J. White Jr., The IAPS formulation for the thermodynamic properties of ordinary water substance for scientific and general use, IAPS (Sep. 1984).

[5] L. Haar, J. Gallagher and G. Knell, NBX/NRC steam tables. Thermodynamic and transport properties and computer programs for vapour and liquid states of water in SI units (McGraw-Hill International, Toronto, 1984).

LIGHT WATER APPROXIMATIONS - ERRATA

"Approximate Functions for the Fast Calculation of Light-Water Properties At Saturation",

by Wm. J. Garland and J. D. Hoskins,
International Journal of Multiphase Flow, Vol. 14, #3, pp 333-348, May-June/1988

1. p.346, under the heading "Dynamic viscosity, liquid phase at saturation": The units given "[10^(-6) kg/(m.s)]" could also be read as: [MPa.s]
2. p.346, "Visc(l) = 64.0-0.00261596*exp(0.4010038)*P" (last equation of the section) should read Visc(l) = 64.0-0.00261596*exp(0.4010038 *P)
3. p.346, the equation for Visc(l) in the range of 18.868 MPa <= P < 20.430 MPa (second last equation of the section) has a maximum error of 0.50% in this range.

"Simple Functions for the Fast Approximation of Light Water Thermodynamic Properties",

by W. J. Garland and B. J. Hand,
Nuclear Engineering and Design, Vol 113, pp 21-34, 1989.

1. p.26, sec 4.4, the last equation of the section has a range given as:
   "18.079 MPa <= P(s) <= 20.300 MPa"; this should read
   "18.079 MPa < P(s) <= 21.500 MPa"; (note TWO changes)
   however, the computer codes that have been released set the pressure to 18 MPa if the given pressure is higher than 18 MPa. Thus the value that will be returned will be erroneous. In addition, the ranges given should be:
   "0.030 MPa < P(s) <= 0.671 MPa"
   "0.671 MPa < P(s) <= 2.606 MPa"
   "2.606 MPa < P(s) <= 6.489 MPa"
   "6.489 MPa < P(s) <= 11.009 MPa"
   "11.009 MPa < P(s) <= 14.946 MPa"
   "14.946 MPa < P(s) <= 18.079 MPa"
   "18.079 MPa < P(s) <= 21.500 MPa"
2. p.27, sec 5.2 the equation for h(P, T) is given. The denominator of one of the fractions reads:
   "SQRT(7.4529x10^(-0.6)*T^(3) - P^(2))"; this should read
   "SQRT(7.4529x10^(-6)*T^(3) - P^(2))"
3. p.27, sec 5.2 the third range equation,
   "h(g)=-7.835986(3.001-P)^(2.0) + 2.934312(3.001-P) + 2803.71" should read
   "h(g)=-7.835986(P-3.001)^(2.0) - 2.934312(P-3.001) + 2803.71" (for the sake of consistency)
4. p.27, sec 5.2 the second last equation,

"h(g)=-3.532177(P-8.00)^(2.0) + 29.81305(P-8.00) + 2.565.00" should read
"h(g)=-3.532177(P-8.00)^(2.0) + 29.81305(P-8.00) + 2565.00"

5. p.28, sec 5.3, the first range given reads:
   "for 0.025 MPa <= p <= 1.480 MPa;" but should read:
   "for 0.025 MPa <= P <= 1.480 MPa;"

6. p.28, sec 5.4, the passage that reads
   "They are valid in the range from 0.070 MPa - 20.4 MPa, and from saturation to 400 C. The error is less than 5%." should read:
   "The equations given are valid in the range from 0.050 MPa - 20.4 MPa, and from saturation to 400 C. When the pressure is above 0.070 MPa, the error is less than 5%; when the pressure is less than 0.070 MPa, the error is slightly higher than 5%."

7. p.29, equation 12 reads "(dF/dP) (T const) + (dF(g)/dP) ..."
   but should read "(dF/dP) (T const) = (dF(g)/dP) ..."

8. p.29, equation 13 has the final term
   "(dR/dT) (T const) * [T-T(P)]" but should read
   "(dR/dT) (P const) * [T-T(P)]"

9. p.32, Appendix I, the equations given have been updated in the third paper (Garland et al) and the user should note the corrections below.

10. p.33 Appendix III, the subcooled equations given under the specific volume section are actually equations for density (the inverse of specific volume). The superheated equations are correct as stated.

11. p.33 Appendix III, the superheated (dv/dP)T equation has, in its final term,
    "(0.12/(T+100)-0.00106)P^(-1.1)" in the numerator; this should read
    "(0.12/(T+100)-0.00106)P^(1.1)"

12. p.33 Appendix III, the superheated (dv/dT)P equation has, in the first part of its second term,
    "(0.12/(T+100))P^(-0.1)" in the numerator; this should read
    "(0.12/(T+100)^2)P^(0.1)" Note there are TWO changes given here.

13. p.33 Appendix III, the superheated (dv/dT)P equation has, in the second part of its second term,
    "(0.12/(T+100)-0.00106)P^(-0.1)" in the numerator; this should read
    "(0.12/(T+100)-0.00106)P^(0.1)"

14. p.33 Appendix III, the superheated (dh/dP)T equation has, in its second term,
    "0.28exp(-0.008(T-162))*(-100/T)"; this should read
    "0.28exp(-0.008(T-162))-100/T"

15. p.33 Appendix III, the superheated (dh/dT)P equation has, in its second term,
    "0.28exp(-0.008(T-1762))"; this should read
    "0.28exp(-0.008(T-162))"

16. p.34 Appendix III, the superheated (ds/dP)T equation has, in its second term,
    " [.... - 4.125x10^(-6) - T + 0.0052]"; this should read

" [.... - 4.125x10^(-6)*T + 0.0053]" (note there are TWO corrections)

17. p.34 Appendix III, the subcooled (ds/dT)P equation has, in its second term,
"dP/dT* (dS/dT + 0.325/(370-T) - 0.004)"; this should read
"dP/dT* (dS/dP + 0.325/(370-T) - 0.004)".

"Extensions to the Approximation Functions for the Fast Calculation of Saturated Water Properties",

by Wm. J. Garland, R. J. Wilson, J. Bartak, J. Cizek, M. Stasny and I. Zentrich,
Nuclear Engineering and Design, # 136, pp 381-388, 1992.

1. p.384, Table A-1, Saturation pressure is given as a function of temperature. The ranges should be corrected as follows:
"17.511 <= T <= 56.275" should be "17.511 <= T < 56.275";
"203.662 <= T < 299.407" should be "203.662 <= T <= 299.407";
"299.407 <= T < 355.636" should be "299.407 < T < 355.636"
to make them consistent with the computer code.

2. p.386, Note 3 of Table A-6, the equation reads
"C(P)=38485636.1747-7311152.45563P+520882.9814112P^(2)+16494.9064728P^(3)+195.89852
but should read
"C(P)=38485636.1747-7311152.45563P+520882.9814112P^(2)-16494.9064728P^(3)+195.89852
Note also that these equations have NOT been implemented in the computer code generated by Dr. Garland.

Back to H2O Home Page

This site was constructed by Jeff Colgan at Dr. William Garland's lab. Please direct any comments toDr. Garland.

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H_2O Property Library

- Fortran library
  H2OPROP.LIB
- 55 subroutines and functions
- based on 1984 NRC/NBS steam tables
- subcooled, saturated, superheated
- ρ, v, h, s, e, c_p, ν
- fast, reasonably curve fits

H_2O Property Library

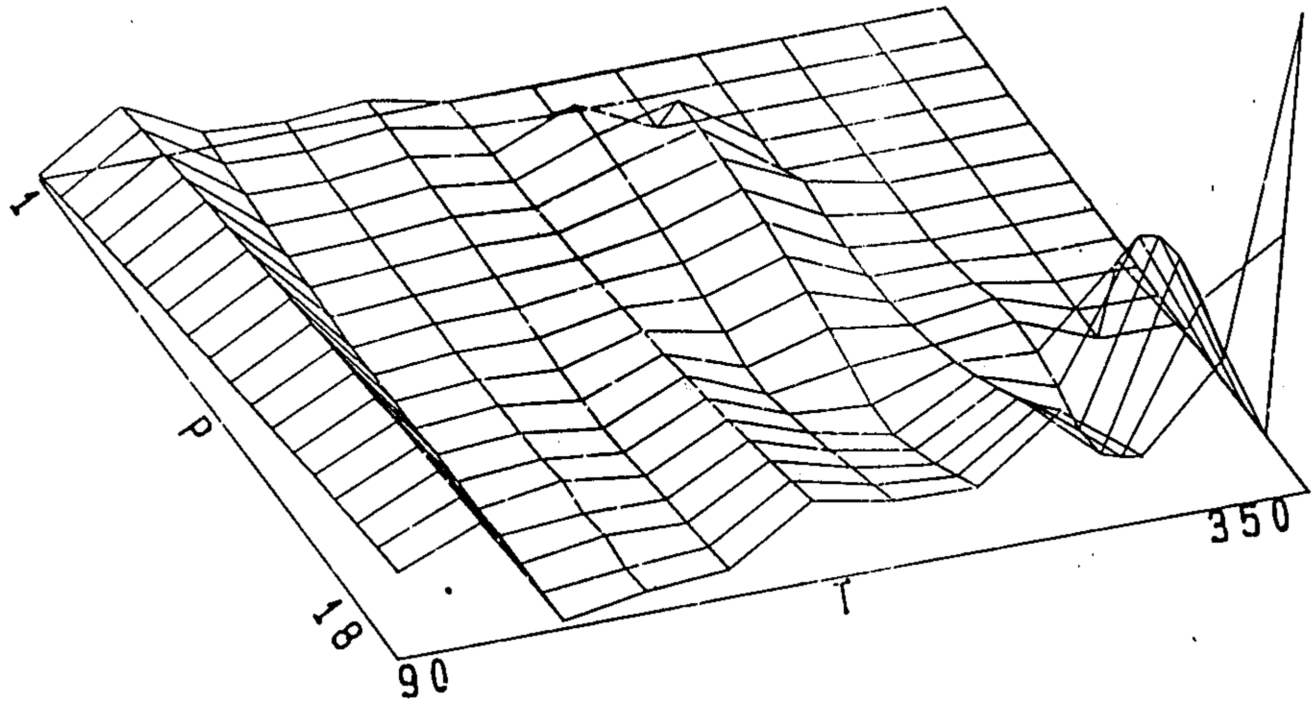
- Library divided into 3 levels:

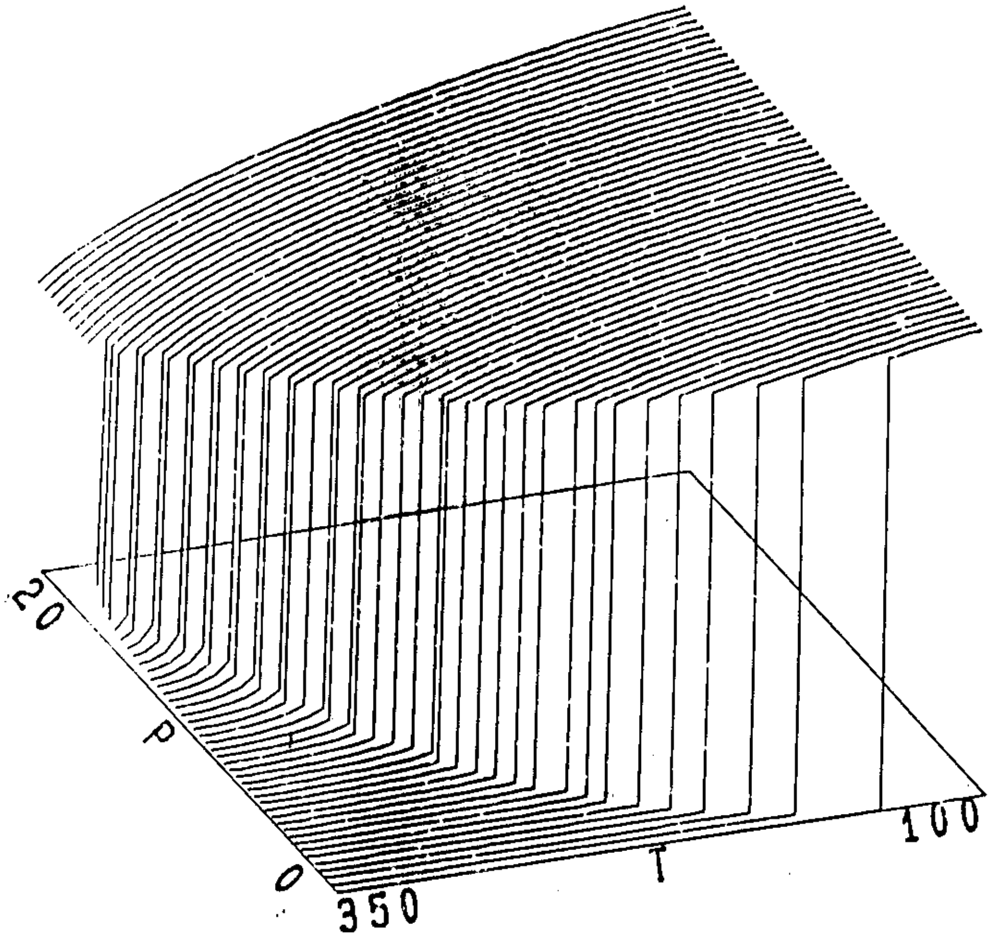
1: fitted functions and slopes
DF(P) DFSUB(P,T), etc.

2: derived functions and collections of functions
SAT(P,ITYPE) SUB(P,T), etc.

3: Logic sorter and manager
PROP(P,T,ISAT,ITYPE........)

ERROR IN THE LIQUID DENSITY, 0.5% max.





DENSITY

Level 1 Fitted functions & slopes

Saturated:

$T_{sat}(P)$ $P_{sat}(T)$

v_f ρ_g $(\rho_f \quad v_g)$

h_f h_g

s_f s_g

C_{pf} C_{pg}

ν_f ν_g

$\left.\frac{\partial T}{\partial P}\right)_{sat}$ $\left.\frac{\partial P}{\partial T}\right|_{sat}$

$\frac{\partial h_f}{\partial P}$ $\frac{\partial h_g}{\partial P}$

$\frac{\partial v_f}{\partial P}$ $\frac{\partial v_g}{\partial P}$

Subcooled	Superheat
ρ_f	v_g $(\nu_f \quad \rho_g)$
h_f	h_g
s_f	s_g
C_{pf}	C_{pg}
$\left.\frac{\partial \rho_f}{\partial P}\right)_T, \left.\frac{\partial \rho_f}{\partial T}\right)_P$	~ for ρ_g
~ for h_f	~ for h_g

Level 2 Calc. all prop. given phase
and either (P, T)
or $(P/T, \rho/h/x/\alpha)$

SAT (P, ITYPE)

- calc. sat$^{\underline{ed}}$ v_f, v_g, h_f, h_g based on P
  also s, e, ρ_f, ρ_g.

ITYPE:

0 : extend not known ∴ $x = \alpha = \rho = h = \ldots\ldots =$
just return v_f, v_g, h_f, h_g etc.

1 : ρ known $\longrightarrow \alpha \longrightarrow v \rightarrow x \longrightarrow h$

2 : h known $\longrightarrow x \rightarrow v \rightarrow \rho \rightarrow \alpha$

3 : x known $\rightarrow v \rightarrow \rho \rightarrow \alpha$
$\searrow h$

4 : α known $\rightarrow \rho \rightarrow v \rightarrow x \rightarrow h$

Finally calc: M, H, E, S, slopes, F & G functn

LEVEL 2

SUB (P,T)

subcooled

∴ directly calc v_f
h_f
⋮
etc.

set $v = v_f$
$h = h_f$
⋮

set $v_g = 0$
⋮

calc M, H, etc.

calc slopes & F & G functions

~ for SUP (P,T) ⟸ superheated.

Also supplied are seperate F & G functions and CLIP routines for T, P, h ∴ ρ.

LEVEL 3 Manager

```
CALL PROP(P, T, ISAT, ITYPE, IFLAG,
          NMAX, ERRTOL, ERRMSG)
```

specify independent variables by :

ISAT =	0	P, T
	1	P sat$^{\underline{ed}}$
	2	T sat$^{\underline{ed}}$
	3	ρ, h
	4	ρ, P
	5	ρ, T
	6	h, P
	7	h, T

for saturated case :

ITYPE =	0	extent	unknown
	1	ρ	known
	2	h	"
	3	x	"
	4	α	"

IFLAG	0	subcooled	derived by program.
	1	saturated	
	2	superheated	

Property values held in a common block.

PROP

calc $P_{sat}(T)$ & $T_{sat}(P)$ as ref. points

clip P, T, h, ρ

Branch on ISAT (0, 7)

0: P, T given, phase unknown

check whether subcooled, superheated or saturated based on $P \Leftrightarrow P_{sat}$

set phase flag and call SAT, SUB or S

1: P, ITYPE saturated

$T = T_{sat}(P) \rightarrow$ call SAT (P, ITYPE)

2: T, ITYPE saturated

$P = P_{sat}(T) \rightarrow$ call SAT (P, ITYPE)

3: ρ & h given

Use P & T as starting guess.

Based on P, calc h_f & h_g & determine ph

Calc slopes & update P & T

iterate

4: similar to 3 above

↓

7:

OTHER Derived properties supplied:

coeff. of vol. expansion

$$\beta = \frac{1}{v} \left.\frac{\partial v}{\partial T}\right)_P$$

isothermal compressibility

$$k = -\frac{1}{v} \left.\frac{\partial v}{\partial P}\right)_T$$

heat capacity

$$C_v = \left.\frac{\partial u}{\partial T}\right)_v = C_p - \frac{\beta^2 T v}{k}$$

Speed of sound

$$c^2 = \left.\frac{\partial P}{\partial \rho}\right)_s = \frac{C_p / T}{\frac{C_p}{T} \left.\frac{\partial \rho}{\partial P}\right)_T - \left[v \left.\frac{\partial \rho}{\partial T}\right)_P \right]^2}$$

Reasonable for 1ϕ liq.

Flakey for 1ϕ vap.

not sure of definitions for 2ϕ

To: STHB staff

From: G.R. M^{c}Gee

WATER PROPERTIES IN EXCEL

I have created an Excel template containing function modules to calculate water properties. This template has been stored in a new shared area, X:\STHB_STM. The template is named MACH2O.XLT, and is recommended to anyone using Excel to analyse thermalhydraulic data.

The functions use correlations developed by Bill Garland, M^{c}Master University. These are the same correlations used in the MYSTEAM steam table utility (also available in X:\STHB_STM; see RC-989 for documentation). Separate functions are provided for subcooled, saturated, and superheated properties. Additional 'general' functions are provided that call the appropriate state-specific routine (based on the input T_{in} and P_{in}), but the user must supply a quality (X_{in}) if the fluid is saturated. The function names, required input and output values, and ranges of validity are listed in the attached table.

To use the functions in an Excel workbook, you need to copy the template (MACH2O.XLT) to your C:\MSOFFICE\EXCEL\XLSTART directory (or whatever directory you have set as the startup directory in Excel). Then when you choose New from the File menu, MACH2O will appear in the template list. If you choose MACH2O, a new workbook will be created (usually called MACH2O1.XLS) which you can use to perform the required analysis or calculations, then rename using "save as".

To enter a property value in a formula, select the Function Wizard button (or select Function from the Insert menu), followed by "User Defined" under function category. An alphabetic list of all the functions appears under Function Name. Double click on the desired function name (for example PSAT). A dialog box appears requesting the required input (for example T_{in}). Either a value (eg. 236.0), cell address (eg. A23) or formula (eg. A23-273.2) can be entered. The routines all contain internal checking logic to screen for invalid inputs. If possible, the invalid input value is reset to the nearest limit (i.e., HGSUP(2.0, 600.0) = HGSUP(2.0, 450.0) = 3363.6). Otherwise, an rude message is generated (i.e., HGSUP(2.0, 20.0) = #NUM!). General property functions can be forced to return saturation values by setting either P_{in} or T_{in} to 0.

Correlations are available for other properties, such as entropy or viscosity. These can be added to the template as required. I also have correlations that could be used to set up similar templates for D_2O or HB-40.

If you have any questions or comments on the template, or require help setting it up, give me a call.

FUNCTION ROUTINES IN EXCEL TEMPLATE MACH2O.XLT

Property	Units	Subcooled Liquid	Saturated	Superheated Vapour	General
Specific Volume	m^3/kg	VFSUB(P_{in}, T_{in})	VF(P_{in}) VG(P_{in})	VGSUP(P_{in}, T_{in})	V(P_{in}, T_{in}, X_{in})
Enthalpy	kJ/kg	HFSUB(P_{in}, T_{in})	HF(P_{in}) HG(P_{in})	HGSUP(P_{in}, T_{in})	H(P_{in}, T_{in}, X_{in})
Specific Heat	kJ/kg	CPFSUB(P_{in}, T_{in})	CPF(P_{in}) CPG(P_{in})	CPGSUP(P_{in}, T_{in})	CP(P_{in}, T_{in}, X_{in})
Thermal Conductivity	W/m-C	AKF(P_{in}, T_{in})		AKG(P_{in}, T_{in})	K(P_{in}, T_{in}, X_{in})
Saturation Pressure	MPa		PSAT(T_{in})		
Saturation Temperature	°C		TSAT(P_{in})		
Ranges:	P_{in}	P_{fg} to18 MPa	0.0006 to 18 MPa	0.002 to 18 MPa	0.002 to 18 MPa
	T_{in}	0.1 to 356°C		T_{fg} to 450°C	0.1 to 450°C
	X_{in}				0 to 1