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Thermophysical Properties of Saturated Light and Heavy Water for Advanced Neutron Source Applications

May 1993

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THERMOPHYSICAL PROPERTIES OF SATURATED LIGHT AND HEAVY WATER FOR ADVANCED NEUTRON SOURCE APPLICATIONS

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May 1993

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NOMENCLATURE

Cond	saturated liquid thermal conductivity (W/m·K)
C_p	saturated liquid specific heat (kJ/kg·K)
DynVisc	saturated liquid dynamic viscosity (Pa·s)
LiqDen	saturated liquid density (kg/m^3)
LqEntl	saturated liquid enthalpy (kJ/kg)
LtnHt	latent heat of vaporization (kJ/kg)
P_{sat}	saturation pressure (MPa)
Sftens	surface tension (N/m)
T_{sat}	saturation temperature (°C)
VapDen	saturated vapor density (kg/m^3)
VapEntl	saturated vapor enthalpy (kJ/kg)

THERMOPHYSICAL PROPERTIES OF SATURATED LIGHT AND HEAVY WATER FOR ADVANCED NEUTRON SOURCE APPLICATIONS

Allen Crabtree
Moshe Siman-Tov

ABSTRACT

The Advanced Neutron Source is an experimental facility being developed by Oak Ridge National Laboratory. As a new nuclear fission research reactor of unprecedented flux, the Advanced Neutron Source Reactor will provide the most intense steady-state beams of neutrons in the world. The high heat fluxes generated in the reactor [303 MW(t) with an average power density of 4.5 MW/L] will be accommodated by a flow of heavy water through the core at high velocities. In support of this experimental and analytical effort, a reliable, highly accurate, and uniform source of thermodynamic and transport property correlations for saturated light and heavy water were developed. In order to attain high accuracy in the correlations, the range of these correlations was limited to the proposed Advanced Neutron Source Reactor's nominal operating conditions. The temperature and corresponding saturation pressure ranges used for light water were 20–300°C and 0.0025–8.5 MPa, respectively, while those for heavy water were 50–250°C and 0.012–3.9 MPa. Deviations between the correlation predictions and data from the various sources did not exceed 1.0%. Light water vapor density was the only exception, with an error of 1.76%. The physical property package consists of analytical correlations, SAS codes, and FORTRAN subroutines incorporating these correlations, as well as an interactive, easy-to-use program entitled QuikProp.

1. INTRODUCTION

The Advanced Neutron Source (ANS) is a new research reactor facility being developed by Oak Ridge National Laboratory (ORNL) to meet the national need for an intense steady-state source of neutrons for scientific experiments. The ANS facility will include a new nuclear fission research reactor of unprecedented flux that will provide the most intense steady-state beams of neutrons in the world. The core of the reactor is composed of parallel aluminum-cladded fuel

plates in an involute geometry. The high heat fluxes generated in the reactor [303 MW(t) with an average power density of 4.5 MW/L] will be accommodated by a flow of heavy water through the core at very high velocities. In support of the Advanced Neutron Source Reactor (ANSR), several test facilities have been built that will simulate the conditions expected in the reactor core. Many of the thermal-hydraulic (T/H) correlations involved in the ANSR design can be derived, modified, or verified using data from these facilities.

In support of this experimental and analytical effort, it was essential to develop a reliable, highly accurate, and uniform source of thermodynamic and transport properties, especially for saturated light and heavy water to be used consistently throughout the project. After surveying the literature and realizing the heavy dependance upon computer programs for ANS calculations, it was concluded that analytical expressions (correlations) rather than tabulated values would be most useful. In order to attain high accuracy in the correlations, the range of these correlations was limited to the proposed ANSR's nominal operating conditions. The temperature and corresponding saturation pressure ranges used for light water were 20–300°C and 0.0025–8.5 MPa, respectively. For heavy water, the temperature and corresponding saturation pressure ranges were 50–250°C and 0.012–3.9 MPa, respectively. A goal was established to limit the maximum deviation in the correlations (compared with their relative original sources) to 3.0%. In practice, however, a higher accuracy was achieved while using a single correlation for the entire range of each property. Deviations did not exceed 1.0%, except for light water vapor density, for which the error was 1.76%.

To ensure the reliability of the physical property correlations, only well-established sources were used. To avoid variations in the International System of Units (SI) conversions, only data originally tabulated in SI units were used in the correlation development. Light water physical property correlations were partly based on data taken from the American Society of Mechanical Engineers (ASME)[1] steam tables. Where ASME did not provide physical properties in SI units, Keenan et al.[2] steam tables were used instead. Heavy water physical property correlations were based on Atomic Energy of Canada Limited (AECL)[3] tables, with the exception of surface tension. The surface tension correlation was based on data from Vargaftik et al.[4] It is worth noting that Kaizerman, Washolder, and Tomerian[5] developed a functional representation of heavy water properties based on Soviet data that made use of heavy to light water property ratios. It

was decided not to rely on such property ratios in this work but rather develop correlations based directly on the indicated tabulated values.

In the development of the physical property correlations, two software codes were used. TableCurve (Jandel Scientific, Corte Madera, California) was used primarily for determining a best fit equation for each property. SAS (SAS Institute, Inc., Cary, North Carolina) was used to fine tune the correlations and calculate the maximum deviations. These correlations were incorporated into SAS codes for determining physical property data for both light and heavy water. Since many people are not familiar with SAS, FORTRAN subroutines of these correlations were also developed that can be easily appended to other calculational programs requiring physical property data. To eliminate the need for time-consuming data searches, interpolations, and unit conversions, an easy-to-use interactive program combining light and heavy water correlations was developed. QuikProp was written in QuickBASIC (Microsoft Corporation, Redmond, Washington) but is a stand-alone executable file, thus, its use does not require compilation or the availability of QuickBASIC.

Although this effort was conducted in support of the ANS project, it is believed that the physical property correlations and the corresponding computer programs documented in this report are also useful to a broader audience. Some limitations in the correlations do exist, however, and further improvements can be made, as recommended in Sect. 6.

2. CORRELATION DEVELOPMENT

In the development of the physical property correlations, several data sources were investigated to determine their reliability. The data sources and ranges selected as well as any difficulties or constraints involved in the development of the physical property correlations are discussed in this section. Explanations concerning any reservations regarding confidence levels or source selections are also included in this section.

2.1 LIGHT WATER CORRELATION DEVELOPMENT

The light water physical property correlations are applicable over a temperature range of 20–300°C and a corresponding saturated pressure range of 0.0025–8.5 MPa. These light water physical property correlations are partly based on data taken from the ASME[1] steam tables. The surface tension correlation is an exact formulation as recommended by ASME. Where ASME did not provide physical properties in SI units, Keenan et al.[2] steam tables were used. Each correlation, its respective source, and maximum deviation from the data are further documented in Sect. 3. The light water physical property correlations developed deviate no more than 0.7% when compared with tabulated values of their respective sources, with the exception of saturated vapor density, which deviates 1.76%.

Most light water physical property correlations were developed using the exact tabulated values with no unit conversions, extrapolations, or interpolations. The development of the liquid dynamic viscosity correlation, however, did require some manipulation. The ASME values are not tabulated for saturated conditions but rather as a function of both temperature and pressure. Of these values, only nine were within the applicable range of the correlation. In order to determine the liquid dynamic viscosity at saturation conditions, two successive viscosity values at a given temperature were used to extrapolate back to the saturation pressure conditions corresponding to that temperature.

The light water physical property correlations incorporated all data available from their respective sources over the applicable range. With the exception of liquid dynamic viscosity, ASME values are tabulated in ten-degree intervals, while Keenan et al.[2] values are in five-degree intervals. Consequently, the correlations using Keenan et al.[2] data result in slightly higher statistical confidence levels.

Although an exact formulation as recommended by ASME is used as the surface tension correlation, an attempt was made to reduce the maximum deviation by determining new constants. New constants were determined by narrowing the original range of the correlation to that of the applicable range. Although a maximum deviation of 0.3% was attained using the new constants as opposed to 0.5% using the original, this improvement was not considered appreciable, and the original constants were retained.

2.2 HEAVY WATER CORRELATION DEVELOPMENT

The heavy water physical property correlations are applicable over a temperature range of 50–250°C and a corresponding saturated pressure range of 0.012–3.9 MPa. These heavy water physical property correlations were based entirely on data taken from the Atomic Energy of Canada Limited (AECL),[3] with the exception of surface tension. The surface tension correlation is an exact formulation taken from Vargaftik et al.[4] Each correlation, its respective source, and maximum deviation from the data is further documented in Sect. 3. The heavy water physical property correlations developed deviate no more than 1.0% when compared with the tabulated values of their respective sources.

With the exceptions of liquid thermal conductivity, liquid dynamic viscosity, and surface tension, all of the heavy water physical property correlations were developed using the exact tabulated values as given in the AECL tables, with no unit conversions, extrapolations, or interpolations. The liquid thermal conductivity values found in the AECL source are not tabulated for saturated conditions but rather as a function of both temperature and pressure. Of these values, only six were within the applicable range of the correlation. In order to determine the liquid thermal conductivity at saturation conditions, two successive conductivity values at a given temperature were used to extrapolate back to the saturation pressure conditions corresponding to that temperature.

In the development of the heavy water liquid dynamic viscosity correlation, it was discovered that the AECL tables did not include values for dynamic viscosity but instead provided two kinematic viscosity tables.[6] In the absence of dynamic viscosity tables, it was first necessary to determine the saturated kinematic viscosity and then convert to dynamic viscosity by multiplying by the corresponding density. As with liquid thermal conductivity, the liquid kinematic viscosity values are not tabulated for saturated conditions but rather as a function of both temperature and pressure. Of these values, only six were within the applicable range of the correlation. In order to

obtain the saturated liquid kinematic viscosity at saturation conditions, two successive kinematic viscosity values at a given temperature were used to extrapolate back to the saturation pressure conditions corresponding to that temperature. Once the saturated liquid kinematic viscosity values were obtained, interpolation was required to determine the saturated liquid density for the corresponding saturation temperature. The saturated liquid kinematic viscosity values were then multiplied by their corresponding saturated liquid density values to obtain the saturated liquid dynamic viscosity. To confirm that all of these manipulations were performed correctly, the resulting saturated liquid dynamic viscosity values were compared with values provided by Heiks et al.[7] This comparison showed good agreement within a maximum deviation of 3.0%.

With the exception of surface tension, the heavy water physical property correlations incorporated all of the available AECL data in the applicable range. In most cases, the physical property correlations are based on property values that are tabulated in five-degree intervals. As a result, these correlations often yield statistically higher confidence levels. As previously mentioned, however, the liquid thermal conductivity and liquid dynamic viscosity correlations were based on only six values that were within the applicable range. Although these correlations yield a lower confidence level, this lower level does not reflect badly on the correlations' performance since the data trends are smooth.

3. ANALYTICAL CORRELATIONS

In the following pages, the actual light and heavy water physical property correlations are presented. Although most of the property values are in SI units, it proved to be more convenient to use megapascals and kilojoules instead of the formal SI units of Pascals and joules. The correlations' maximum deviations from the data and their respective sources are listed in Table 1 at the end of this chapter. In order to attain the accuracy as stated in Table 1, the coefficients must be applied exactly as they appear. Any alteration, including truncation, of the coefficients will cause a noticeable change in the accuracy of the resulting property values.

Although the physical property correlations for saturated heavy water were originally developed for a 50–250°C temperature range, we have also examined the correlations' performance over an extended range. The correlations were checked both at 45° and 35°C. A five-degree extension of the temperature range resulted in minor error increases. In some cases, the error at 45°C was lower than the maximum deviation in the original range. The extension of the correlations to 35°C resulted in slight error increases.

Errors were not reported at either temperature for saturated heavy water thermal conductivity and dynamic viscosity because these properties were already valid for temperatures as low as 26.84°C. Errors for saturated liquid specific heat were not reported because there were no data for saturated specific heat below 47.93°C in the AECL[3] data. Although one would not expect a major increase in the error of saturated liquid specific heat at 45°C, it is not known whether the error at 35°C would be small. Where data were available, the maximum deviations were 0.33 and 1.68% at 45 and 35°C, respectively.

3.1 PHYSICAL PROPERTY CORRELATIONS FOR SATURATED LIGHT WATER

The physical property correlations for saturated light water are applicable over a temperature range of 20–300°C. This temperature range corresponds to a pressure range of 0.0025–8.5 MPa.

H_2O SATURATION TEMPERATURE (as a function of pressure)

$$T_{sat} = (A + CX)/(1 + BX + DX^2) , \tag{1}$$

where

X = ln(P),
A = 179.9600321,
B = -0.1063030,
C = 24.2278298,
$D = 2.951 \times 10^{-4}$,

P = absolute pressure (MPa),
T_{sat} (°C).

H_2O SATURATION TEMPERATURE (as a function of saturated liquid enthalpy)

$$T_{sat} = A + Bh + Ch^{5/2} + Dh^3 , \tag{2}$$

where

A = 0.0835777361,
B = 0.2377936769,
$C = 5.1932951 \times 10^{-7}$,
$D = -2.2208153 \times 10^{-8}$,

h = liquid enthalpy (kJ/kg),
T_{sat} (°C).

H_2O SATURATION PRESSURE

$$P_{sat} = exp[(A + CT + ET^2) / (1 + BT + DT^2 + FT^3)] , \quad (3)$$

where

A = -7.395489709,
B = 4.884152×10^{-3},
C = 3.6337285×10^{-2},
D = 4.308960×10^{-6},
E = 2.651419×10^{-5},
F = -4.14934×10^{-9},

T = temperature (°C),
P_{sat} (MPa).

H_2O SATURATED LIQUID ENTHALPY

$$LqEntl = (A + CT + ET^2) / (1 + BT + DT^2) , \quad (4)$$

where

A = 0.786889159,
B = -0.001874457,
C = 4.163042560,
D = -3.334×10^{-7},
E = -0.007798602,

T = temperature (°C),
LqEntl (kJ/kg).

H_2O LATENT HEAT OF VAPORIZATION

$$LtnHt = (A + BT + CT^2 + DT^3)^{1/2} , \quad (5)$$

where

A = 6254828.560,
B = -11742.337953,
C = 6.336845,
D = -0.049241,

T = temperature (°C),
LtnHt (kJ/kg).

H_2O SATURATED VAPOR ENTHALPY

$$VapEntl = A + BT^{5/2} + CT^3 + DT^{1/2}[ln(T)] \ , \tag{6}$$

where

A = 2488.301071,
B = 6.2698272×10^{-4},
C = -3.953072×10^{-5},
D = 3.562872385,

T = temperature (°C),
VapEntl (kJ/kg).

H_2O SATURATED VAPOR DENSITY

$$VapDen = (A + CT + ET^2 + GT^3)/(1 + BT + DT^2 + FT^3 + HT^4) \ , \tag{7}$$

where

A = -4.375094×10^{-4},
B = -6.947700×10^{-3},
C = 7.662589×10^{-4},
D = 2.418897×10^{-5},
E = -5.963920×10^{-6},
F = -4.227966×10^{-8},
G = 2.867976×10^{-7},
H = 2.594175×10^{-11},

T = temperature (°C),
VapDen (kg/m^3).

H_2O SATURATED LIQUID DENSITY

$$LiqDen = (A + BT_F + CT_F^2) \ , \tag{8}$$

where

T_F = 1.8T + 32,
A = 1004.789042,
B = -0.046283,
C = -7.9738×10^{-4},

T = temperature (°C),
LiqDen (kg/m^3).

H_2O SATURATED LIQUID THERMAL CONDUCTIVITY

$$Cond = (A + BT + CT^2 + DT^3)\ , \tag{9}$$

where

A = 0.5677829144,
B = 1.8774171×10^{-3},
C = -8.1790×10^{-6},
D = $5.66294775 \times 10^{-9}$,

T = temperature (°C),
$Cond$ (W/m•K).

H_2O SATURATED LIQUID DYNAMIC VISCOSITY

$$DynVisc = exp[(A + CT)/(1 + BT + DT^2)]\ , \tag{10}$$

where

A = -6.325203964,
B = 8.705317×10^{-3},
C = -0.088832314,
D = -9.657×10^{-7},

T = temperature (°C),
$DynVisc$ (Pa•s).

H_2O SATURATED LIQUID SPECIFIC HEAT

$$C_P = [(A + CT)/(1 + BT + DT^2)]^{1/2}\ , \tag{11}$$

where

A = 17.48908904,
B = -1.67507×10^{-3},
C = -0.03189591,
D = -2.8748×10^{-6},

T = temperature (°C),
C_p (kJ/kg•K).

H_2O SURFACE TENSION

$$Sftens = AX^B(1 + CX) \ , \tag{12}$$

where

X = (373.99 - T)/647.15,
A = 235.8×10^{-3},
B = 1.256,
C = -0.625,

T = temperature (°C),
Sftens (N/m).

3.2 PHYSICAL PROPERTY CORRELATIONS FOR SATURATED HEAVY WATER

The physical property correlations for saturated heavy water are applicable over a temperature range of 50–250 °C. This temperature ranges corresponds to a pressure range of 0.012–3.9 MPa.

D_2O SATURATION TEMPERATURE (as a function of pressure)

$$T_{sat} = exp(A + BX + CX^2 + DX^3) \ , \tag{13}$$

where

X = ln(P),
A = 5.194927982,
B = 0.236771673,
C = -2.615268 × 10^{-3},
D = 1.708386 × 10^{-3},

P = absolute pressure (MPa),
T_{sat} (°C).

D_2O SATURATION TEMPERATURE (as a function of saturated liquid enthalpy)

$$T_{sat} = A + Bh[ln(h)] + Ch^2[ln(h)] \ , \tag{14}$$

where

A = 11.34352515,
B = 0.03875871,
C = -5.733 × 10^{-6},

h = liquid enthalpy (kJ/kg),
T_{sat} (°C).

D_2O SATURATION PRESSURE

$$P_{sat} = exp(A + B/T_K + C \times ln(T_K) + DT_K) \ , \tag{15}$$

where

T_K = T + 273.16,
A = 95.720020,
B = -8439.470752,
C = -13.496506,
D = 0.012010,

T = temperature (°C),
P_{sat} (MPa).

D_2O SATURATED LIQUID ENTHALPY

$$LqEntl = A + BT^2 + CT / ln(T) \ , \tag{16}$$

where

A = -81.40815291,
B = 0.00274496,
C = 21.13005836,

T = temperature (°C),
LiqEntl (kJ/kg).

D_2O LATENT HEAT OF VAPORIZATION

$$LtnHt = (A + BX + CX^2)^{1/2} \ , \tag{17}$$

where

X = 371.49 - T,
A = 508093.6669,
B = 17006.921765,
C = -11.009078,

T = temperature (°C),
LtnHt (kJ/kg).

D_2O SATURATED VAPOR ENTHALPY

$$VapEntl = A + BT[ln(T)] + CT^3 \quad , \tag{18}$$

where

A = 2337.404845,
B = 0.335900,
C = -1.30643×10^{-5},

T = temperature (°C),
VapEntl (kJ/kg).

D_2O SATURATED VAPOR DENSITY

$$VapDen = exp[(A + CT + ET^2)/(1 + BT + DT^2)] \quad , \tag{19}$$

where

A = -5.456208705,
B = 2.386228×10^{-3},
C = 0.060526809,
D = -1.15778×10^{-5},
E = -1.11360×10^{-4},

T = temperature (°C),
VapDen (kg/m^3).

D_2O SATURATED LIQUID DENSITY

$$LiqDen = (A + BT_F + CT_F^2) \ , \tag{20}$$

where

T_F = 1.8T + 32,
A = 1117.772605,
B = -0.077855,
C = -8.42×10^{-4},

T = temperature (°C),
LiqDen (kg/m^3).

D_2O SATURATED LIQUID THERMAL CONDUCTIVITY

$$Cond = (A + BT_1 + CT_1^2 + DT_1^3) , \tag{21}$$

where

$T_1 = (1.8T + 491.67) \times 10^{-4}$,
$A = -0.4521496$,
$B = 36.0743280$,
$C = -357.9973221$,
$D = 924.0219962$,

T = temperature (°C),
$Cond$ (W/m•K).

D_2O SATURATED LIQUID DYNAMIC VISCOSITY

$$DynVisc = (A + BT_F + C/T_F + D/T_F2) , \tag{22}$$

where

$T_F = 1.8T + 32$,
$A = -1.111606 \times 10^{-4}$,
$B = 9.46 \times 10^{-8}$,
$C = 0.0873655375$,
$D = 0.4111103409$,

T = temperature (°C),
$DynVisc$ (Pa•s).

D_2O SATURATED LIQUID SPECIFIC HEAT

$$C_P = (A + BT_1 + CT_1^2 + DT_1^3) , \tag{23}$$

where

$T_1 = (1.8T + 491.67) \times 10^{-4}$,
$A = 2.237124$,
$B = 122.217151$,
$C = -2303.384060$,
$D = 13555.737878$,

T = temperature (°C),
C_P (kJ/kg•K).

D_2O SURFACE TENSION

$$Sftens = AX^B(1 + CX) , \tag{24}$$

where

$X = (371.49 - T)/644.65,$
$A = 2.44835759 \times 10^{-1},$
$B = 1.269,$
$C = -6.60709649 \times 10^{-1},$

T = temperature (°C),
Sftens (N/m).

Table 1. Performance of the saturated light and heavy water physical property correlations

Physical property correlation	Light water		Heavy water			
	Maximum deviation (%) 200–300°C	Reference[a]	Maximum deviation (%) 50–250°C	45°C	35°C	Reference[a]
Saturation temperature (function of pressure)	0.28	Keenan[2]	1.00	-	-	AECL[3]
Saturation temperature (function of saturated liquid enthalpy)	0.35	Keenan[2]	0.39	-	-	AECL[3]
Saturation pressure	0.17	Keenan[2]	0.03	0.02	0.06	AECL[3]
Saturated liquid enthalpy	0.16	Keenan[2]	0.17	0.33	1.68	AECL[3]
Latent heat of vaporization	0.03	Keenan[2]	0.31	0.33	0.50	AECL[3]
Saturated vapor enthalpy	0.05	Keenan[2]	0.04	0.06	0.12	AECL[3]
Saturated vapor density	1.76	Keenan[2]	0.29	0.26	0.11	AECL[3]
Saturated liquid density	0.70	Keenan[2]	0.10	0.03	0.10	AECL[3]
Saturated liquid thermal conductivity	0.61	ASME[1]	0.10	-	-	AECL[3]
Saturated liquid dynamic viscosity	0.70	ASME[1]	0.21	-	-	AECL[3]
Saturated liquid specific heat	0.10	ASME[1]	0.10	-	-	AECL[3]
Surface tension	0.50	ASME[1]	0.54	0.03	0.02	Vargaftik[4]

[a]Complete citations are located in sect. 8.

4. PHYSICAL PROPERTY COMPUTER CODES

The physical property correlations were incorporated in three different codes using three different programming languages. The most extensive code was an interactive properties software package that was developed using QuickBASIC. The most versatile code was a pair of FORTRAN subroutines that can be easily appended to any FORTRAN code. The correlations were also organized in a third code providing SAS users a means of determining physical property data.

4.1 QUIKPROP

A convenient, quick, and easy to use interactive properties software package was developed using the physical property correlations. Although written in QuickBASIC, QuikProp is a stand-alone executable code and does not require QuickBASIC for execution. The correlations used in the code are exactly as they appear in Sect. 3. The program can accept both temperatures and pressures in either British or SI units. No preinstruction is necessary because the user is guided through the program. It was our intent for this program to provide the user with a "quick" source of physical properties, thus alleviating the need for time consuming interpolations and unit conversions.

4.2 FORTRAN SUBROUTINES

FORTRAN subroutines have been developed that can be easily incorporated in existing FORTRAN codes. Usually this requires no more than the addition of a call statement in the original code. As with the interactive properties package, all correlations used in the subroutines are exactly as they appear in Sect. 3. The subroutines calculate physical properties and pass them to the main program as double-precision values. As a word of caution, the subroutines often provide inaccurate values if a double-precision input value is not passed to the subroutine. If single-precision values are desired, the variable declarations statement in the physical property subroutines must be changed accordingly.

4.3 SAS PROGRAMS

Unlike FORTRAN, SAS is not a very common programming language. SAS, however, was used in the development of the physical property correlations, and as a result, the first physical property codes were written in SAS. As with all the other physical property codes, the correlations used in their development are exactly as they appear in Sect. 3. The initial point, final point, and interval are defined at the top of the code using macro variables. The properties are then calculated, and the results are displayed in the output window in a tabular format.

The authors will be glad to provide a copy of these codes upon request. If you are interested, please contact Allen Crabtree [(615) 576-5298] or Moshe Siman-Tov [(615) 574-6515].

5. PHYSICAL PROPERTY TABLES AND GRAPHS

The tables and graphs in this section are provided as an additional description of the correlations and their performance. Table 2 is followed by Figs. 1-10 for selected saturated light water properties, while Table 3 is followed by Figs. 11-20 for selected saturated heavy water properties. The tables are sample outputs from the property codes described in Sect. 4 and are not suggested for uses other than point calculations or comparisons. As a visual representation of the physical property correlations, the graphs reflect any trends that the properties may have as a function of temperature. The computer codes described in Sect. 4 are highly recommended for any additional computations and are readily available from the authors. If these codes are not adequate for a particular application and the user wishes to incorporate the correlations himself, the sample output results will serve as an excellent means of checking accuracy.

Table 2. Sample output of the saturated light water correlations[a]

T_{sat} (°C)	P_{sat} (MPa)	LqEntl (kJ/kg)	LtnHt (kJ/kg)	VapEntl (kJ/kg)	VapDen (kg/m^3)	LiqDen (kg/m^3)	Cond (W/m·K)	DynVisc (Pa·s)	C_p (kJ/kg·K)	Sftens (N/m)
20	0.00234	84.092	2454.00	2536.84	0.01700	997.955	0.60210	0.0010051	4.17804	0.072738
35	0.00563	146.619	2418.57	2566.09	0.03998	993.196	0.62372	0.0007190	4.17824	0.070405
50	0.01235	209.226	2382.73	2593.00	0.08308	987.274	0.64191	0.0005453	4.18143	0.067947
65	0.02503	271.953	2346.24	2618.71	0.16097	980.190	0.65681	0.0004320	4.18789	0.065369
80	0.04738	334.846	2308.85	2643.60	0.29310	971.944	0.66853	0.0003538	4.19801	0.062676
95	0.08454	397.956	2270.30	2667.70	0.50450	962.534	0.67718	0.0002976	4.21221	0.059874
110	0.14326	461.344	2230.32	2690.90	0.82657	951.963	0.68287	0.0002555	4.23105	0.056966
125	0.23207	525.079	2188.58	2712.95	1.29790	940.228	0.68572	0.0002232	4.25519	0.053960
140	0.36129	589.242	2144.76	2733.55	1.96501	927.331	0.68585	0.0001977	4.28548	0.050861
155	0.54315	653.93	2098.49	2752.34	2.8831	913.272	0.68337	0.00017715	4.32297	0.047676
170	0.79168	719.25	2049.35	2768.92	4.1172	898.050	0.67839	0.00016030	4.36901	0.044412
185	1.12271	785.34	1996.90	2782.85	5.7435	881.665	0.67103	0.00014625	4.42539	0.041078
210	1.90623	897.65	1900.62	2798.97	9.5774	851.773	0.65379	0.00012745	4.54905	0.035387
225	2.54767	966.69	1836.50	2803.59	12.7396	832.289	0.64064	0.00011825	4.64689	0.031911
240	3.34414	1037.28	1766.62	2803.82	16.7287	811.641	0.62554	0.00011025	4.76899	0.028401
255	4.31931	1109.78	1690.00	2799.13	21.7417	789.831	0.60858	0.00010322	4.92364	0.024874
270	5.49861	1184.63	1605.35	2789.02	28.0410	766.858	0.58990	0.00009701	5.12363	0.021345
285	6.90937	1262.40	1510.99	2772.93	35.9898	742.723	0.56960	0.00009147	5.38994	0.017835
300	8.58104	1343.84	1404.61	2750.33	46.1091	717.425	0.54780	0.00008649	5.75973	0.014368

[a]See Nomenclature (p. vii).

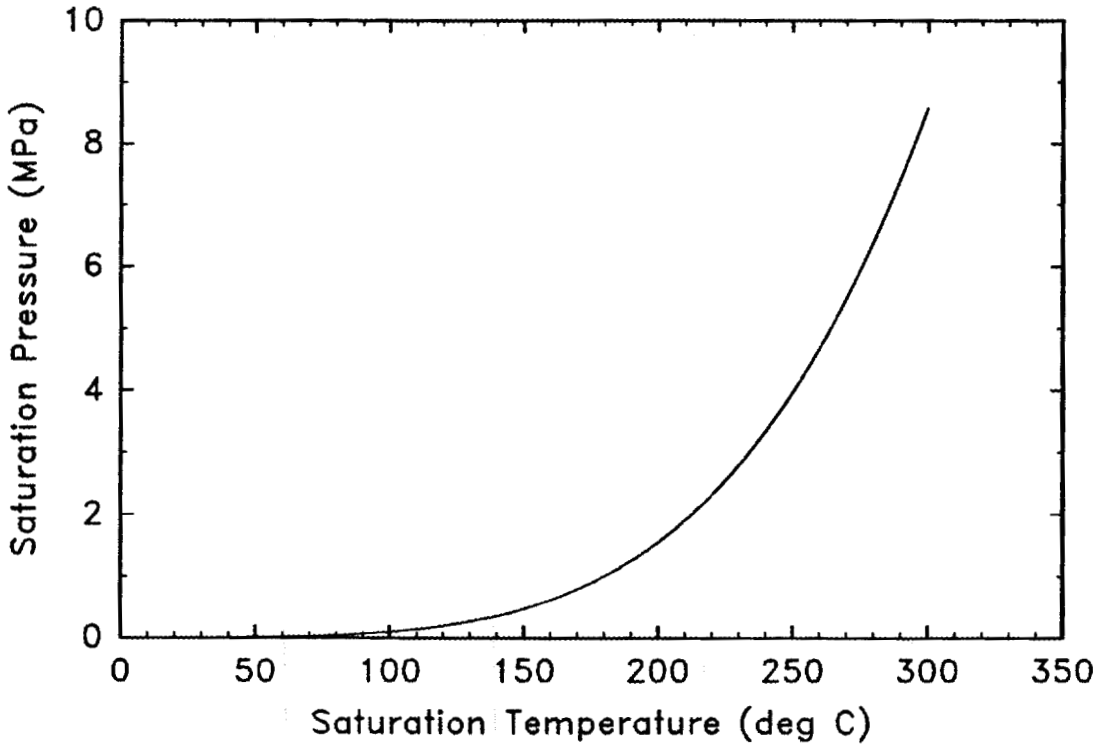

Fig. 1. H_2O saturation pressure using Eq. 3.

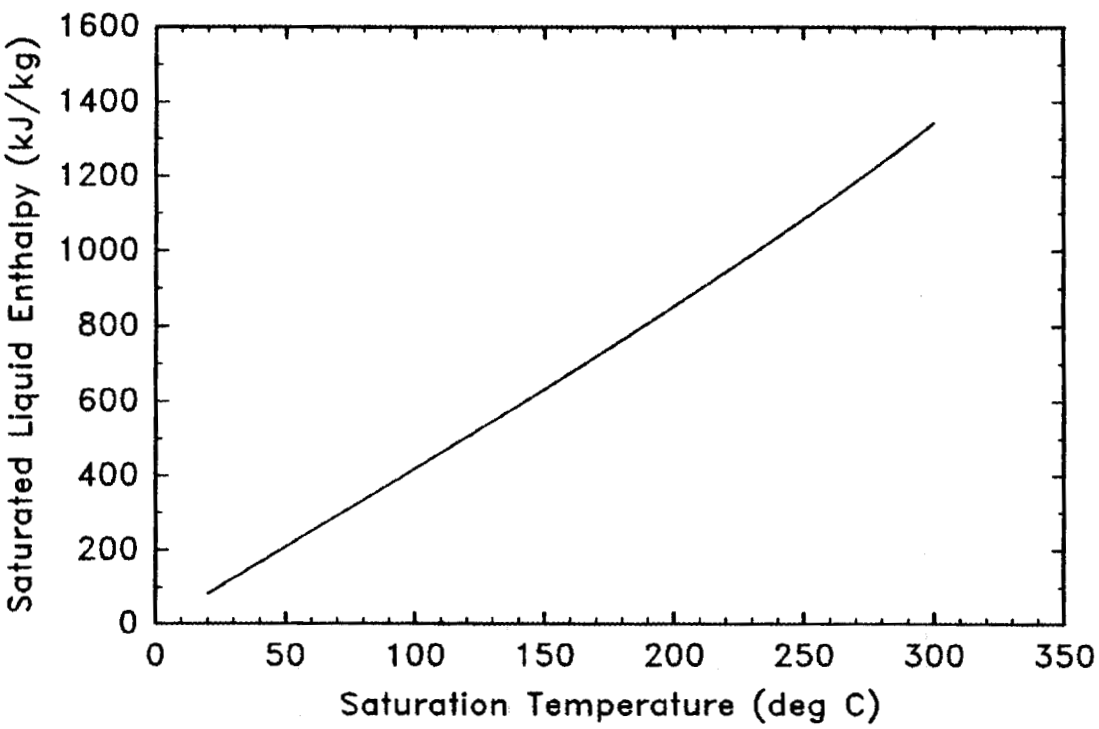

Fig. 2. H_2O saturated liquid enthalpy using Eq. 4.

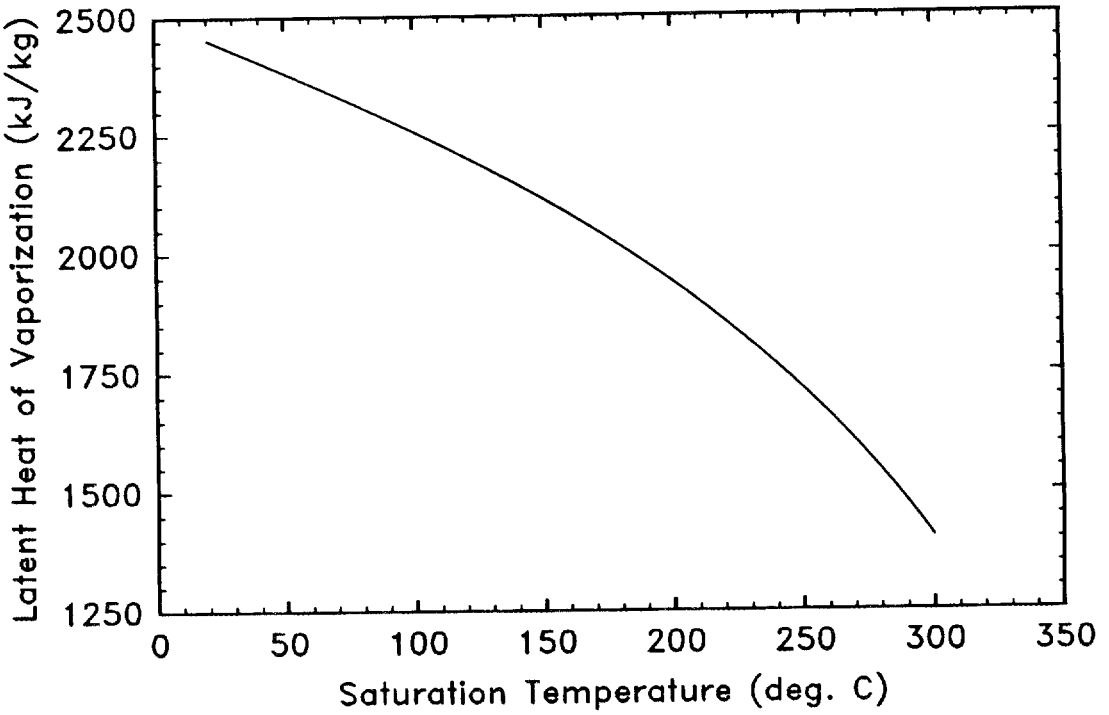

Fig. 3. H_2O latent heat of vaporization using Eq. 5.

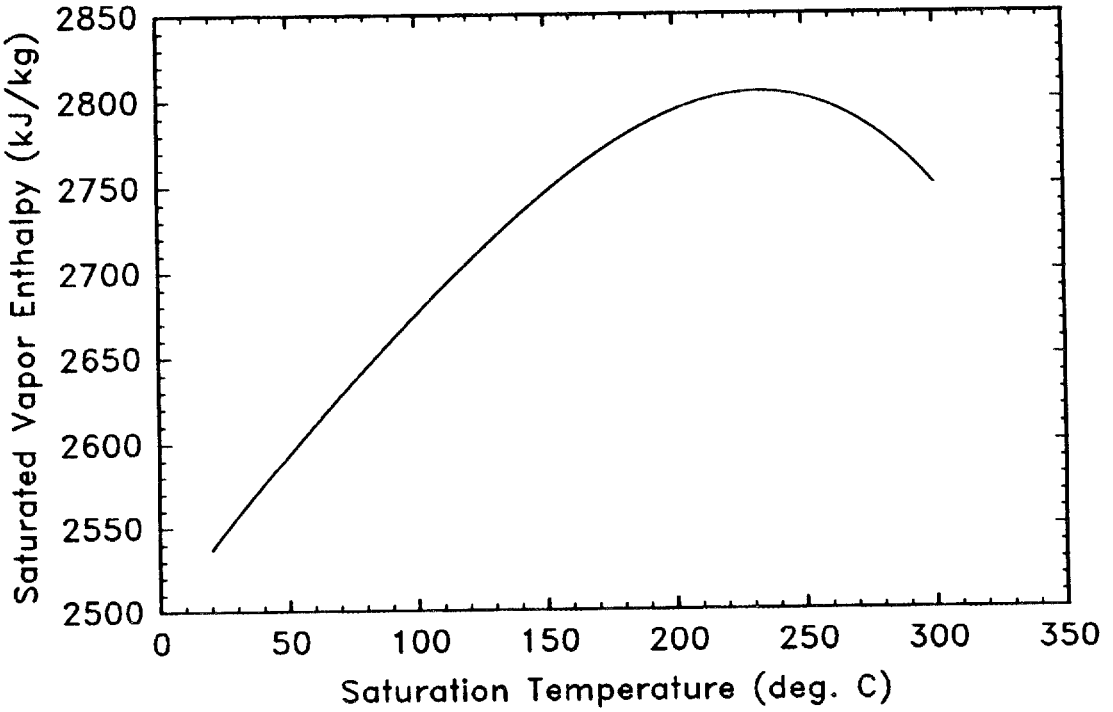

Fig. 4. H_2O saturated vapor enthalpy using Eq. 6.

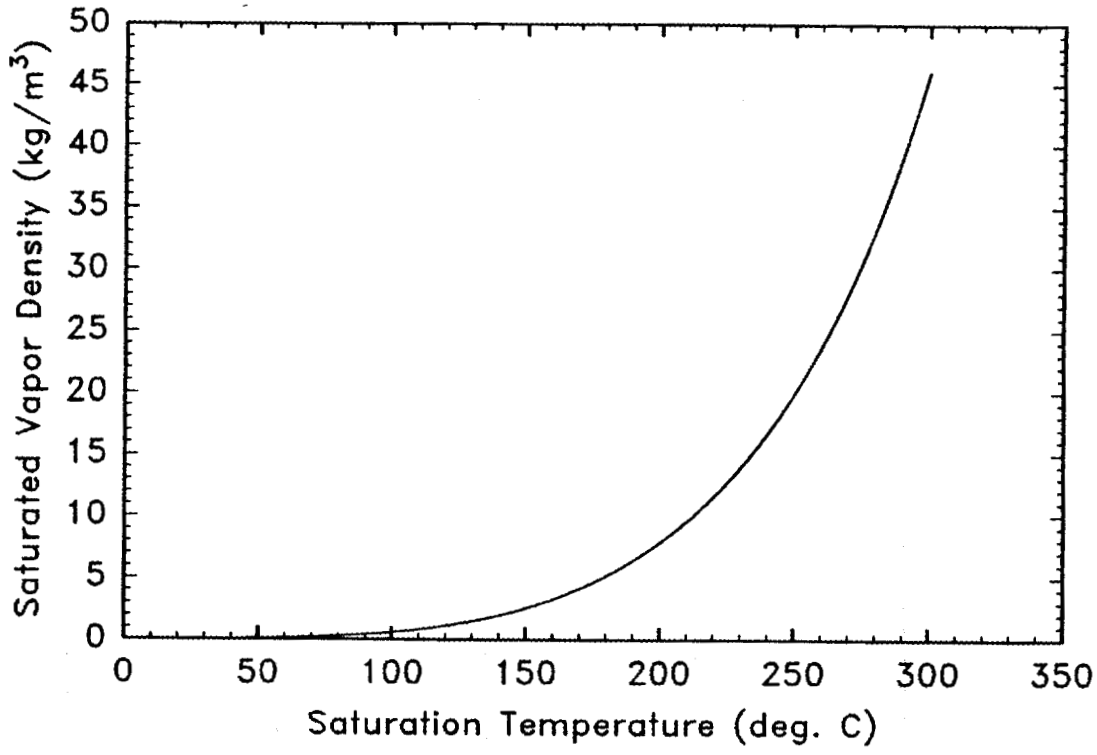

Fig. 5. H_2O saturated vapor density using Eq. 7.

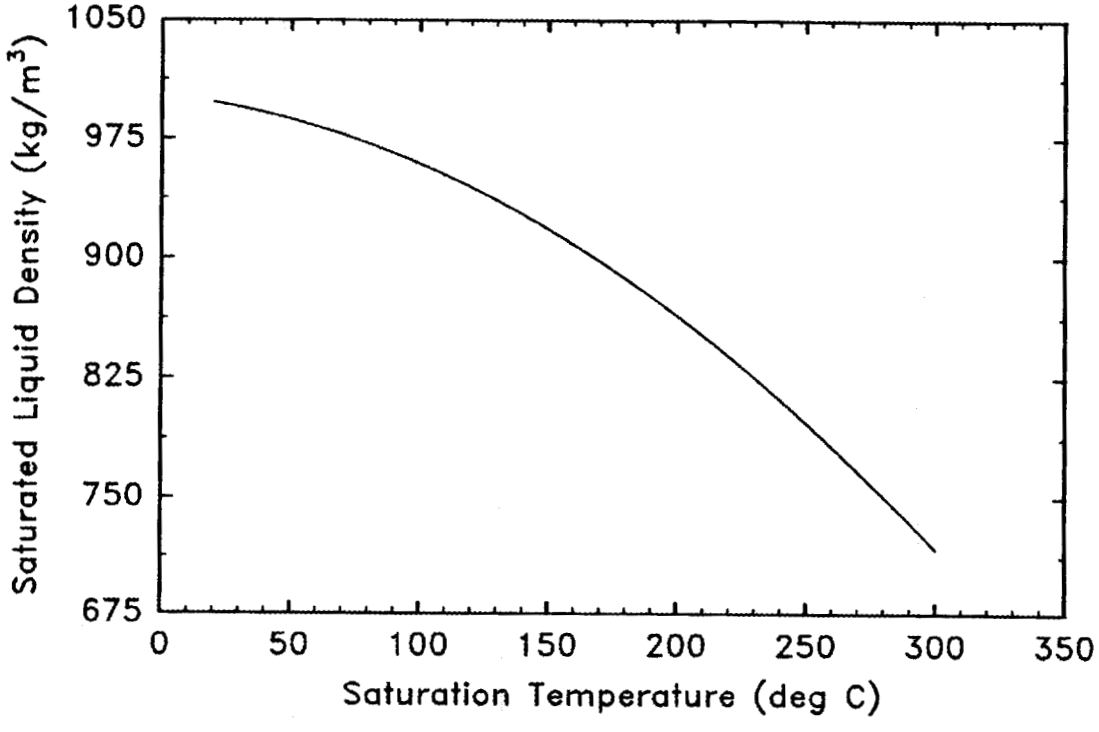

Fig. 6. H_2O saturated liquid density using Eq. 8.

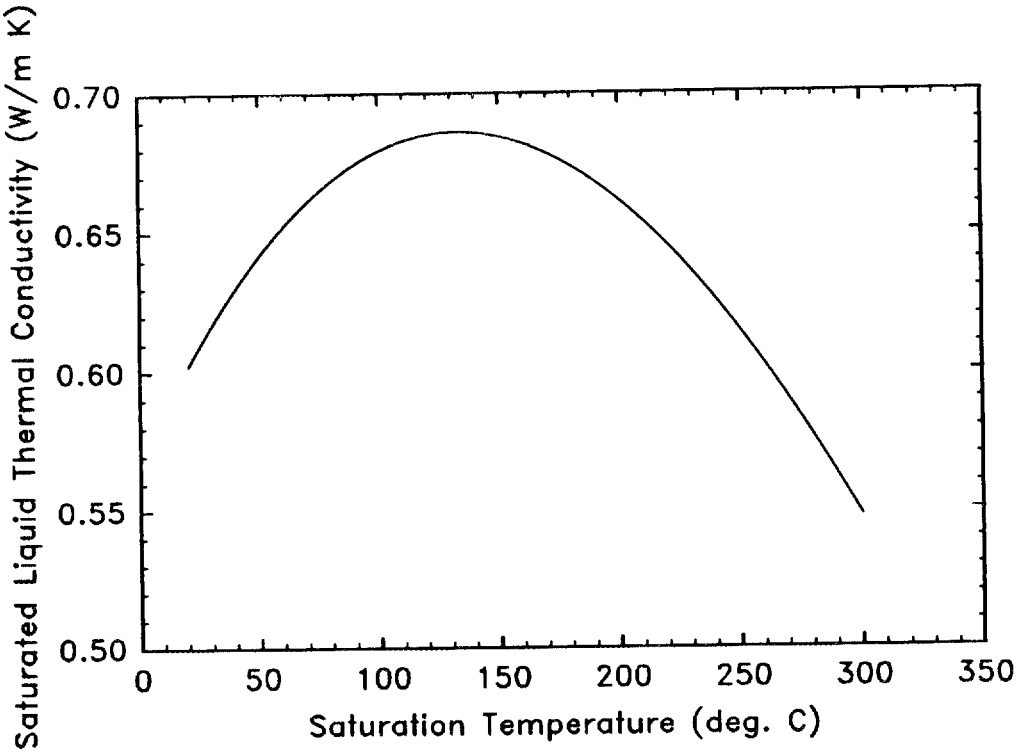

Fig. 7. H_2O saturated liquid thermal conductivity using Eq. 9.

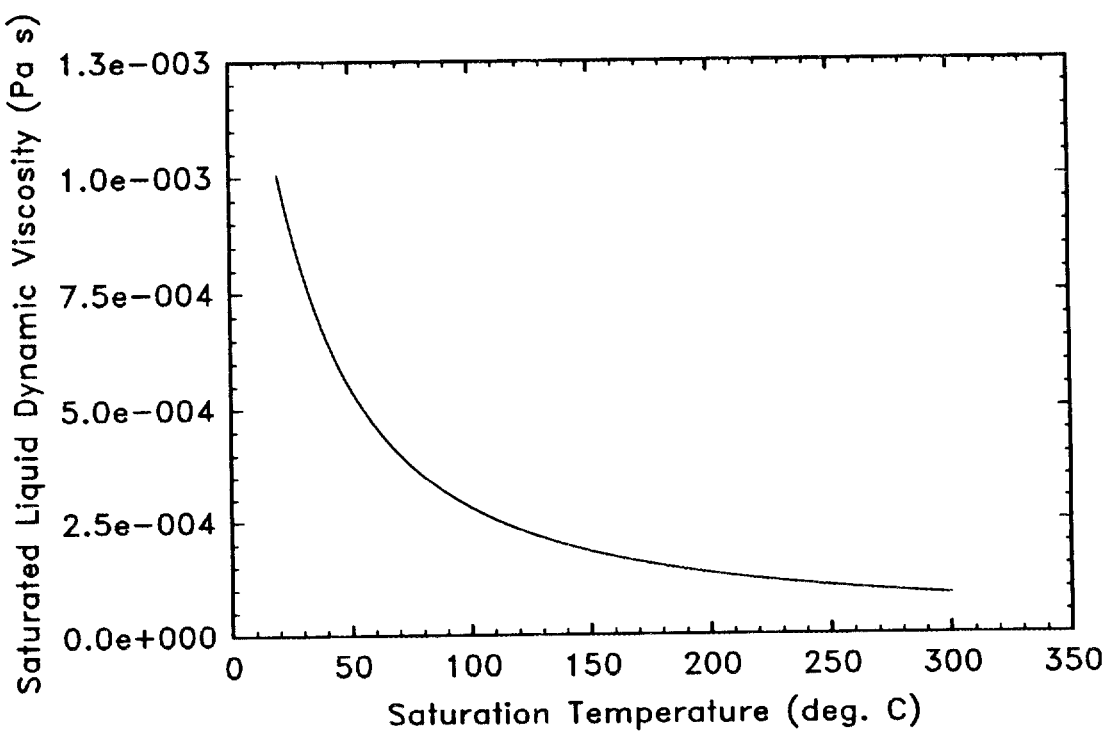

Fig. 8. H_2O saturated liquid dynamic viscosity using Eq. 10.

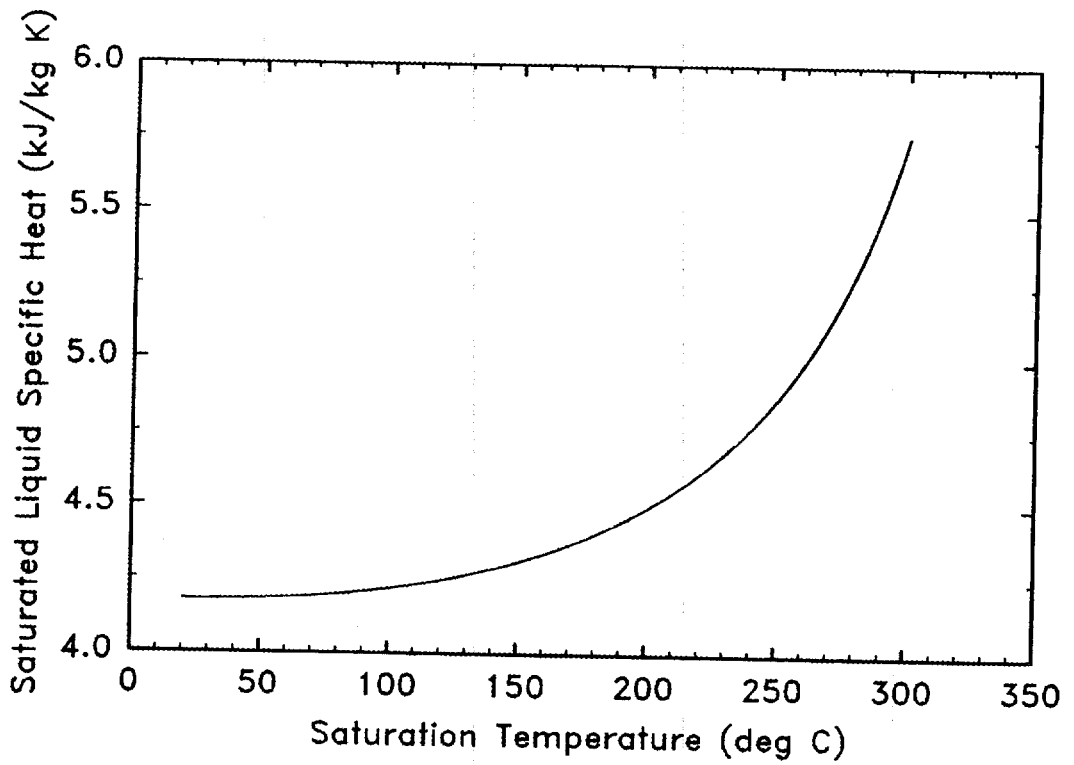

Fig. 9. H_2O saturated liquid specific heat using Eq. 11.

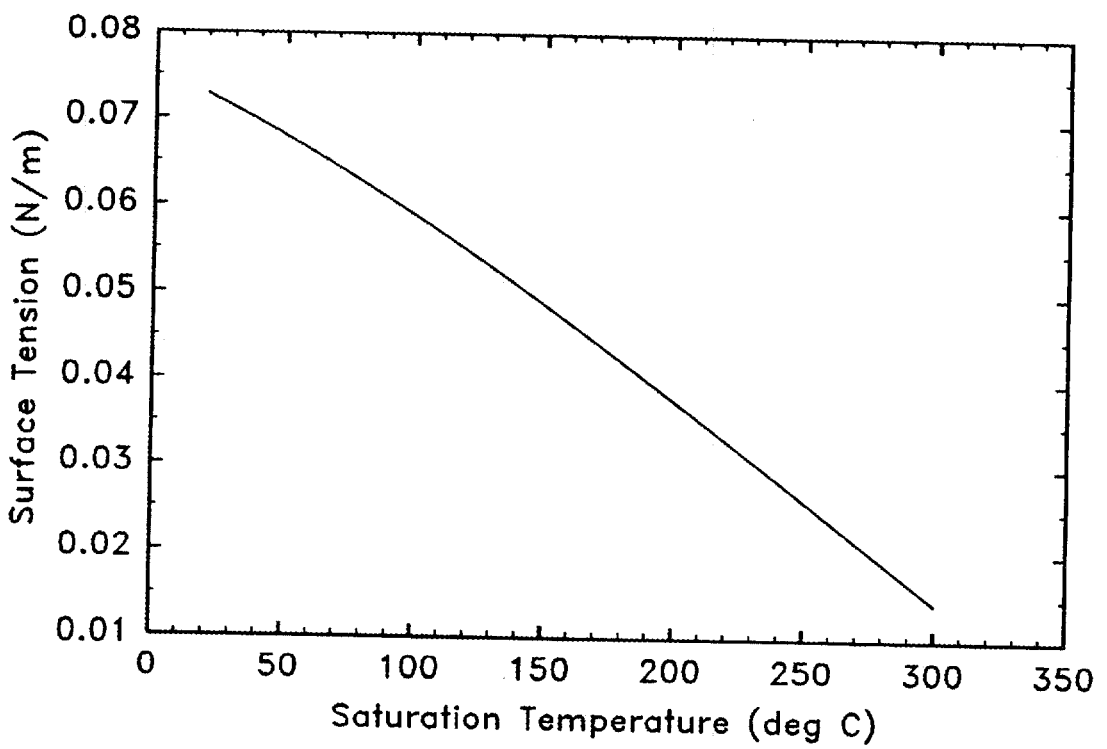

Fig. 10. H_2O surface tension using Eq. 12.

Table 3. Sample output of the saturated heavy water correlations[a]

T_{sat} (°C)	P_{sat} (MPa)	LqEntl (kJ/kg)	LtnHt (kJ/kg)	VapEntl (kJ/kg)	VapDen (kg/m^3)	LiqDen (kg/m^3)	Cond (W/m·K)	DynVisc (Pa·s)	C_p (kJ/kg·K)	Sftens (N/m)
50	0.01112	195.520	2199.50	2401.47	0.08342	1095.74	0.61679	0.00064411	4.22066	0.067895
65	0.02299	259.209	2164.81	2424.96	0.16510	1087.48	0.62565	0.00050780	4.19937	0.065366
80	0.04422	321.918	2128.39	2448.47	0.30483	1077.99	0.63175	0.00041516	4.18059	0.062708
95	0.07997	384.167	2090.15	2471.52	0.53060	1067.27	0.63520	0.00034839	4.16591	0.059927
110	0.13703	446.289	2049.99	2493.69	0.87825	1055.32	0.63611	0.00029822	4.15695	0.057030
125	0.22405	508.517	2007.80	2514.62	1.39210	1042.15	0.63458	0.00025932	4.15529	0.054022
140	0.35159	571.022	1963.43	2533.94	2.12568	1027.75	0.63074	0.00022843	4.16254	0.050911
155	0.53215	633.931	1916.75	2551.34	3.14249	1012.12	0.62468	0.00020343	4.18030	0.047704
170	0.78017	697.347	1867.58	2566.49	4.51720	995.26	0.61651	0.00018289	4.21018	0.044410
185	1.11196	761.35	1815.72	2579.09	6.3375	977.180	0.60635	0.00016581	4.25377	0.041037
200	1.54564	826.00	1760.92	2588.83	8.7073	957.868	0.59430	0.00015147	4.31267	0.037596
215	2.10105	891.37	1702.91	2595.43	11.7518	937.329	0.58048	0.00013933	4.38848	0.034098
230	2.79969	957.48	1641.34	2598.58	15.6260	915.562	0.56499	0.00012898	4.48281	0.030554
245	3.66468	1024.39	1575.80	2598.01	20.5300	892.567	0.54793	0.00012013	4.59726	0.026981
250	3.99420	1046.88	1552.99	2596.94	22.4374	884.630	0.54192	0.00011746	4.64016	0.025785

[a]See Nomenclature (p. vii).

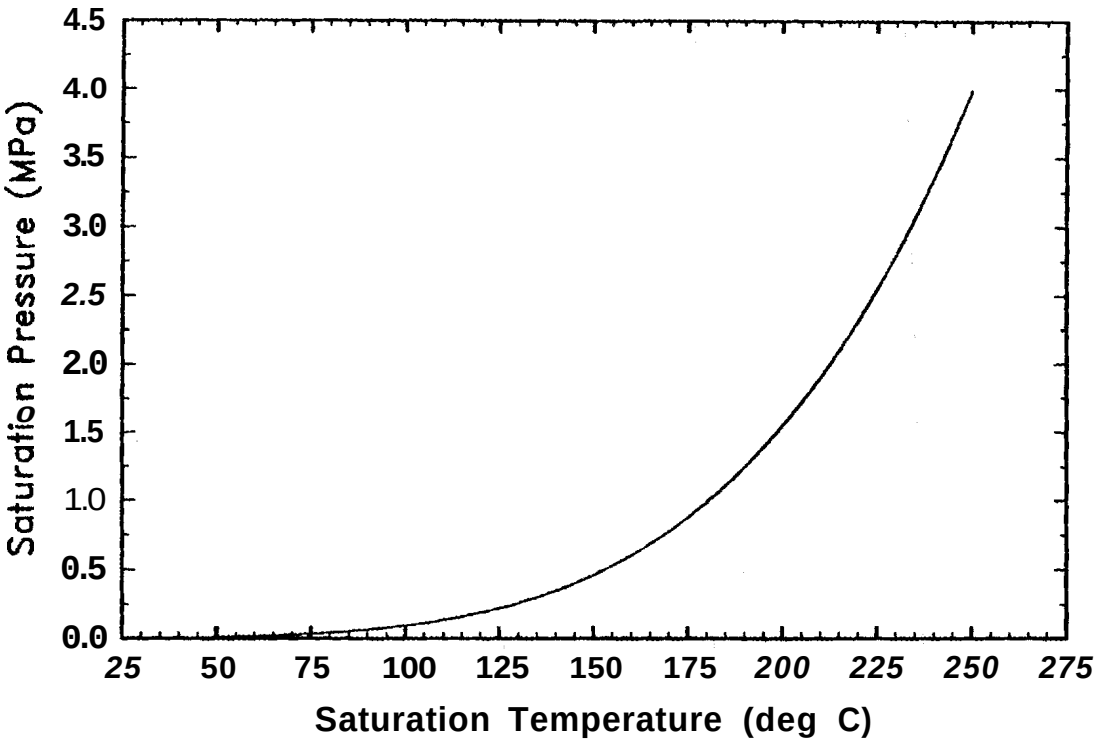

Fig. 11. D_2O saturation pressure using Eq. 15.

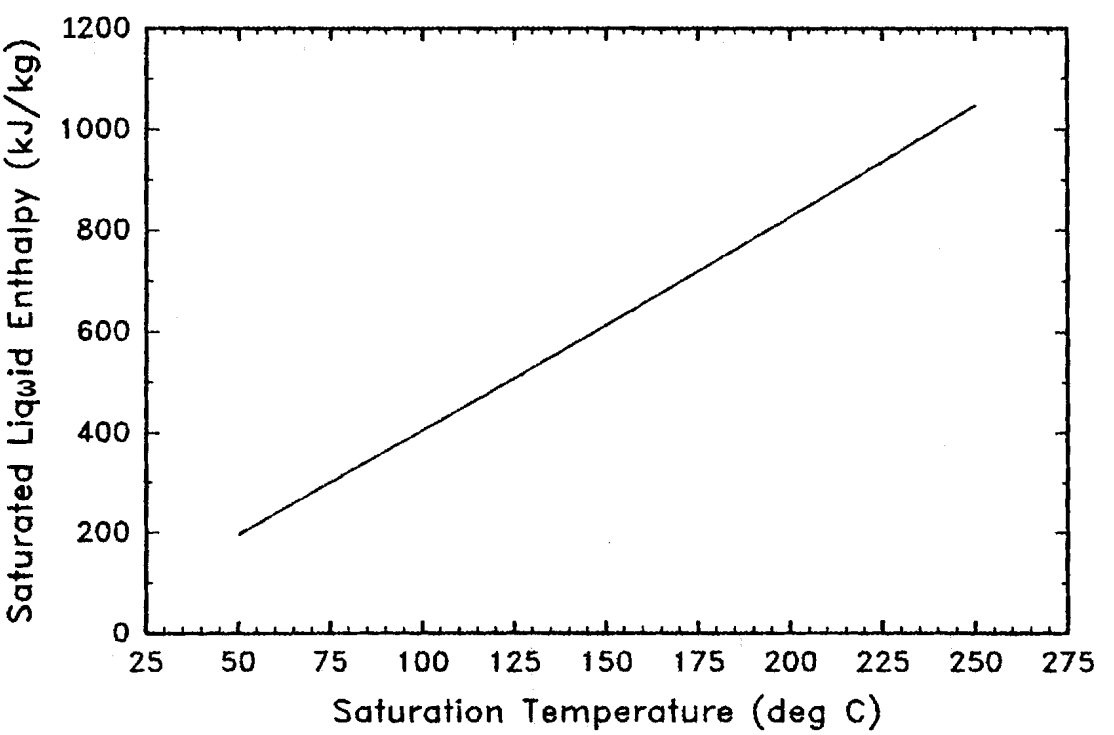

Fig. 12. D_2O saturated liquid enthalpy using Eq. 16.

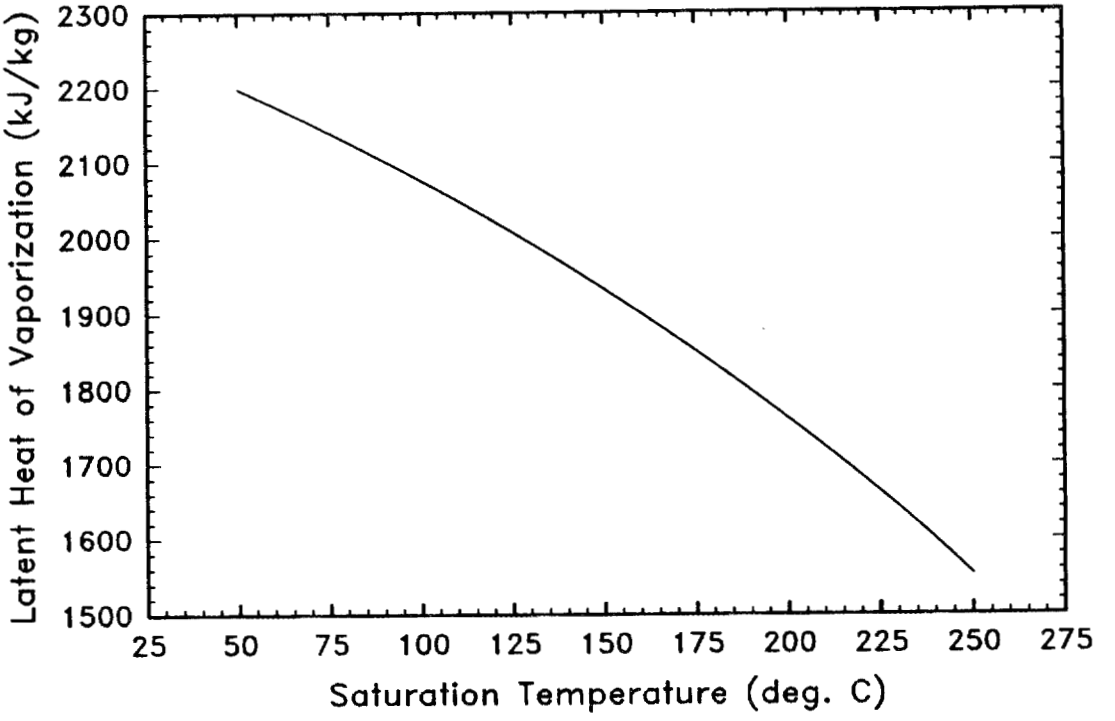

Fig. 13. D_2O latent heat of vaporization using Eq. 17.

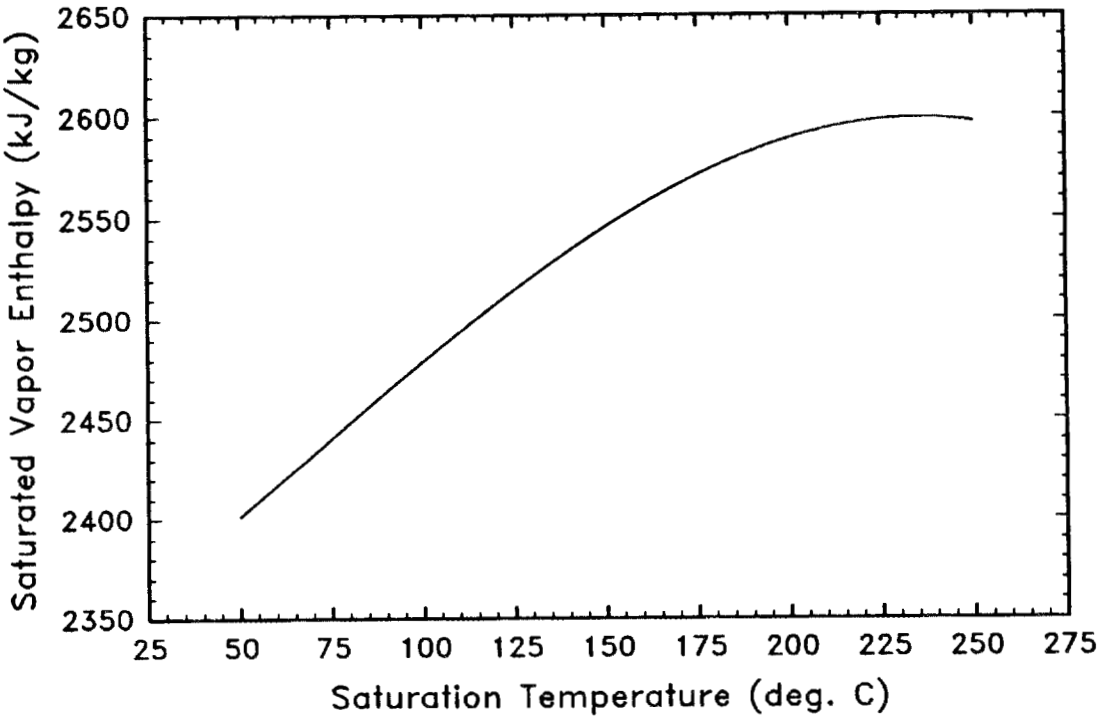

Fig. 14. D_2O saturated vapor enthalpy using Eq. 18.

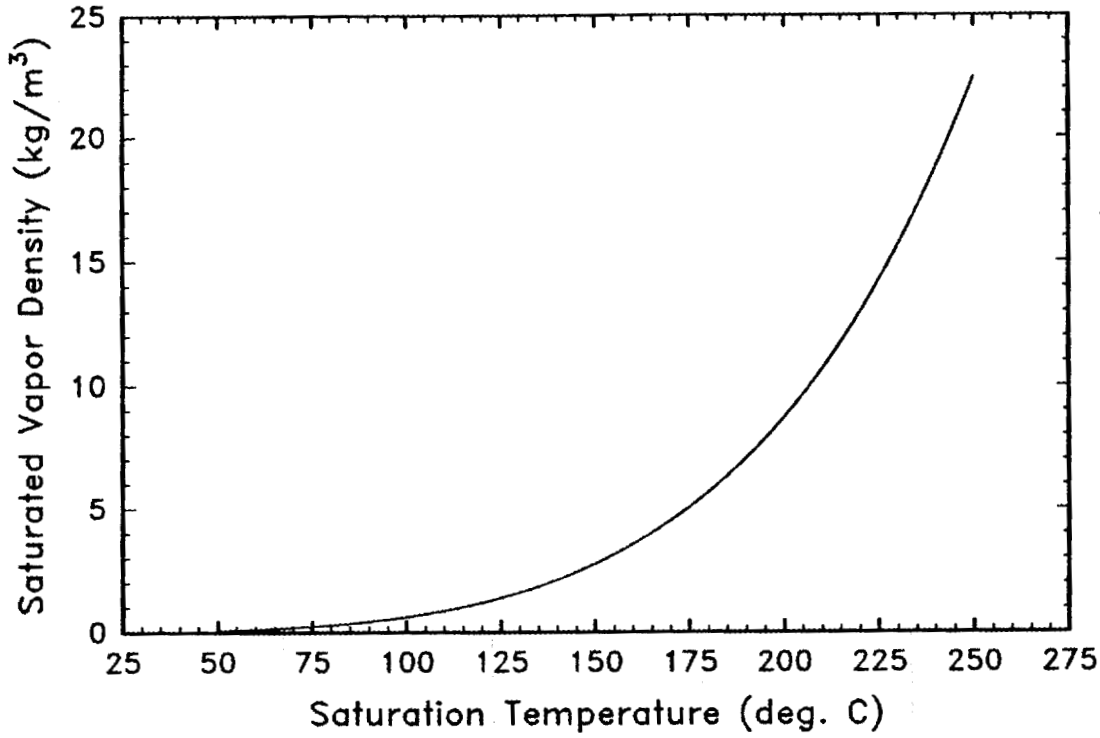

Fig. 15. D_2O saturated vapor density using Eq. 19.

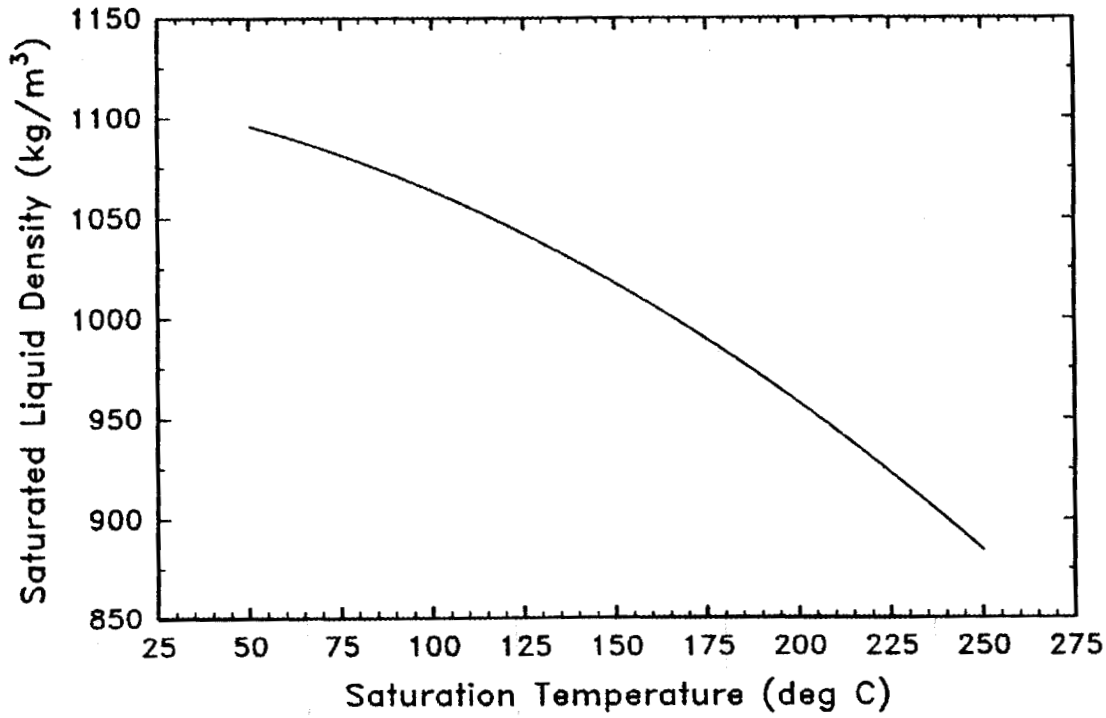

Fig. 16. D_2O saturated liquid density using Eq. 20.

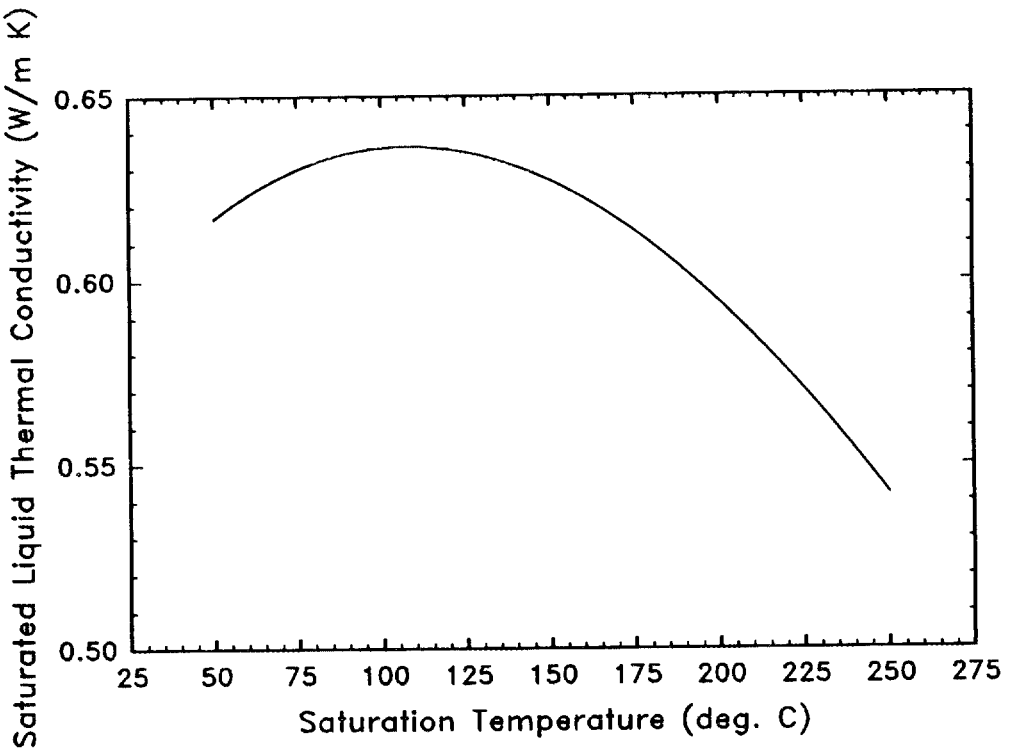

Fig. 17. D_2O saturated liquid thermal conductivity using Eq. 21.

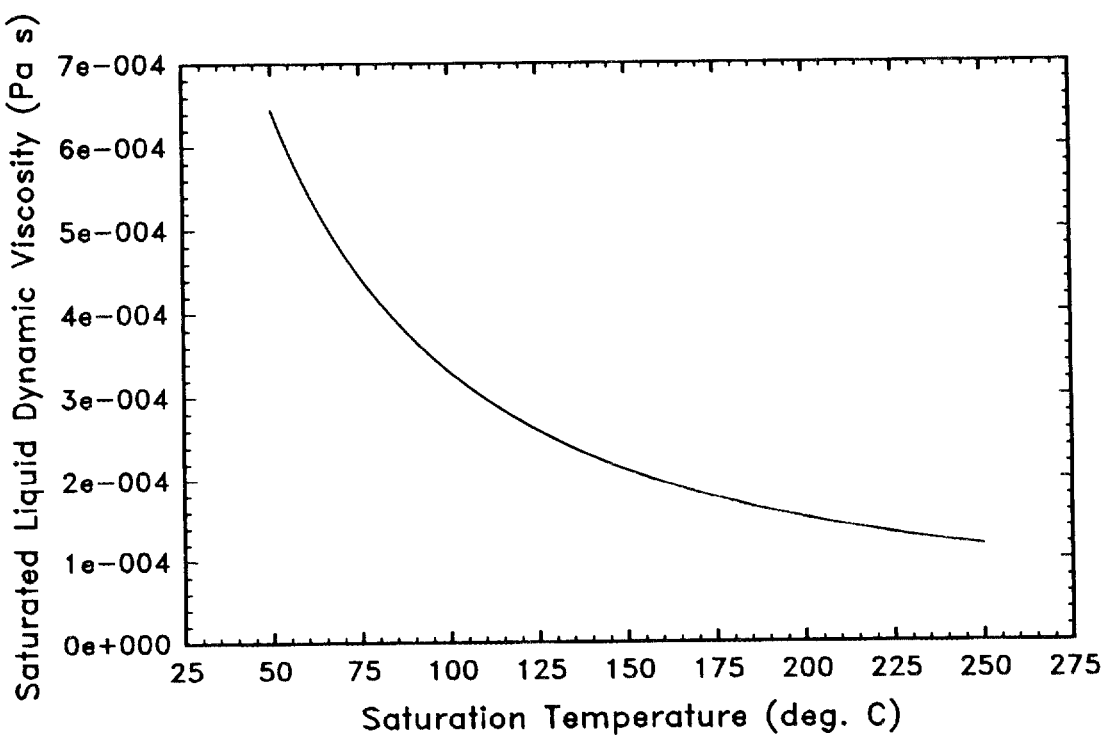

Fig. 18. D_2O saturated liquid dynamic viscosity using Eq. 22.

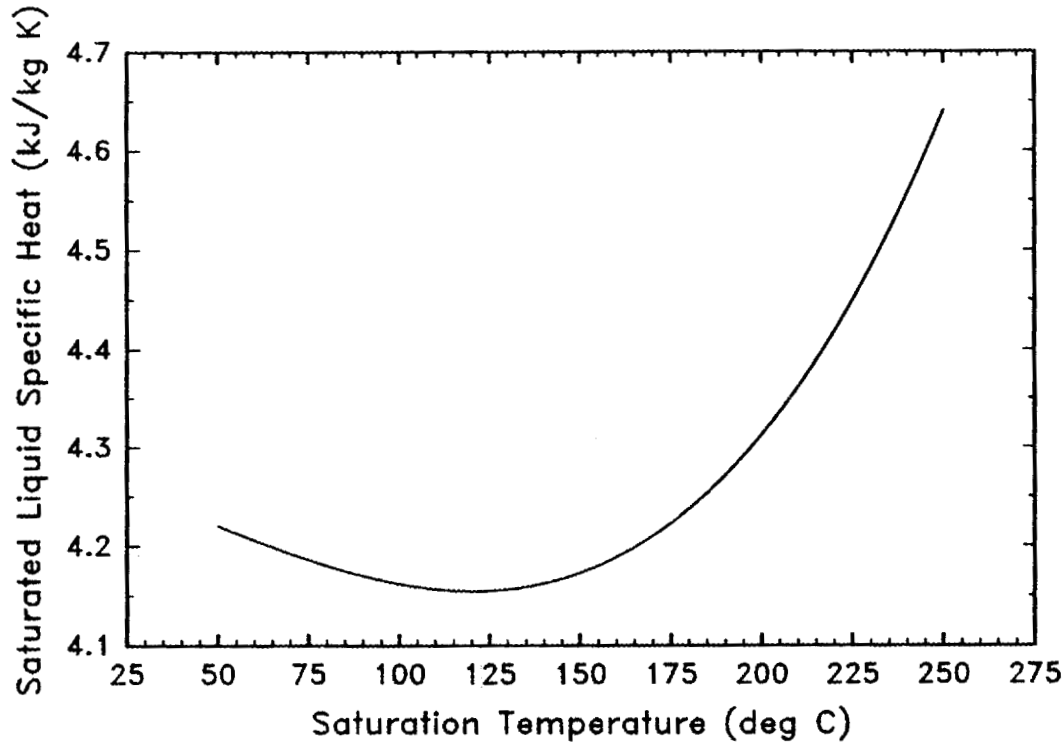

Fig. 19. D_2O saturated liquid specific heat using Eq. 23.

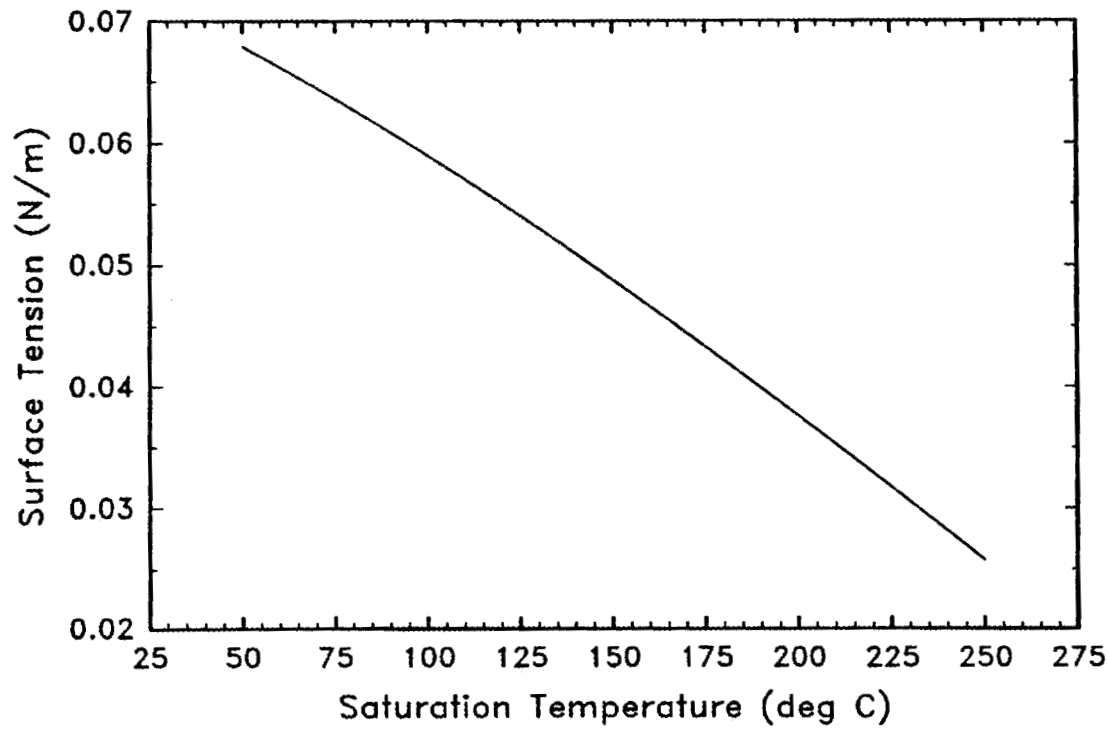

Fig. 20. D_2O surface tension using Eq. 24.

6. RECOMMENDATIONS

The physical property correlations provided in this document are for saturated conditions only, but subcooled conditions will exist in the ANSR. Although subcooled conditions are nominal, local superheated conditions are also possible. As a result, the most prominent recommendation for future work is to determine the error associated with the use of these correlations in calculating properties at subcooled and superheated conditions. The error is not expected to be large since most of the physical properties do not have a strong dependance on pressure. If the resulting error is considered unacceptable, however, additional correlations will be necessary.

The correlation range was originally designed to cover ANSR nominal operating conditions. A need to broaden this range may arise as more safety analyses are performed. Many accident analyses, for example, would require correlation ranges comprising certain off-nominal operating conditions. It may be difficult, however, to maintain the same level of accuracy in a single correlation if the range is much broader.

It is encouraging to know that the interactive program, QuikProp, is actually being used and gaining popularity within the ANS project. As a result, it has been recommended that a Macintosh version of QuikProp be developed. Although the current version of QuikProp can run under Windows as a DOS application, a mouse-driven Windows version is desirable.

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