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The Helmholtz's Potential in the IAPWS-95 Formulation for the Supercritical Conditions of Geothermal Water in an Efficient Graphical Interface

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ABSTRACT

H_2O is one of the fluids that has been the most extensively investigated, both theoretically and experimentally, worldwide. The thermodynamic behavior of water has a crucial importance in a multitude of scientific and industrial applications of geothermal energy. The International Association for the Properties of Water and Steam (IAPWS) is an organization responsible for the international standardization of the thermophysical properties of water. This includes an equation of state of ordinary H_2O for general and scientific use. The IAPWS-95 formulation is based on the Helmholtz's free energy as the fundamental potential that is a function of both the density and the temperature of water. All other thermodynamic properties can be obtained by partial differentiation and algebraic manipulation of the corresponding Helmholtz surface $f(T, \rho)$. We constructed a useful computer code of this formulation for water properties within an interactive graphical interface using the programming language of the software Wolfram Mathematica, version 9. The properties shown in this paper are the most useful in geothermal engineering practice: pressure, specific volume, entropy, enthalpy, internal energy, dynamic and kinematic viscosity, isothermal compressibility, specific heat, and thermal conductivity. These properties are computed separately for each phase, -liquid and vapor- in a wide thermodynamic range. The program also calculates the saturation pressure and temperature in the K-line for two-phase water. All the properties are computed with high numerical precision covering all experimentally measured ranges and reported in the IAPWS-95 formulation. The powerful graphical interface of the program allows immediate display of any of the H_2O properties in 2D and 3D graphics simultaneously. The covered temperatures range from 0°C to 4730°C, and pressures range from 0.1 MPa (1 bar) to 100 GPa (10^6 bar). We used highly efficient algorithms based on the IAPWS-95 formulation. The computer program is original, freely available, and can be used in all types of geothermal systems of low, medium, high and supercritical enthalpy. Examples are presented to illustrate the code for critical and supercritical conditions. The code is useful in practical and theoretical geothermal research, and is a valuable didactic tool for anyone interested in geothermal water properties.

1. INTRODUCTION

Earth is a geothermal system with a huge amount of energy. The heat contained in the interior of the planet is a result of the gradual cooling of the core, and the decay of radioactive elements in the mantle and crust. By conductive and convective processes, the Earth's internal heat flows outward creating various geothermal systems such as deposits of oil and gas, hydrothermal reservoirs, hot dry rock, underwater vents, magma, geopressured systems, volcanic and drinking water aquifers (Suárez, 2000; Bundschuh & Suarez, 2010).

At present, the internal energy of the planet is exploited through the water contained in natural reservoirs or artificially introduced into geothermal systems for purposes ranging from electricity production, industrial purposes, heating, and other so-called direct uses (Rojas, 2013). Depending on the thermodynamic conditions in which the geothermal system is found, the presence of water can be predominantly liquid, predominantly steam, or two-phase. Under appropriate thermodynamic conditions, when water and steam coexist in geothermal reservoirs, we say that fluid is biphasic (Bundschuh & Suarez, 2010). Other geothermal reservoirs have suitable thermodynamic conditions to contain supercritical water.

Water is one of the most important substances in the world. It is required for geothermal energy, and is indispensable for life and various well-known processes. In chemical engineering is the most common solvent. One of its modern uses is the disposal of hazardous wastes in its supercritical state. In nature, water plays a key role in climate change; it covers more than two thirds of the earth's surface and it is of paramount importance to all living organisms. Understanding its properties under extreme temperatures and pressures is essential in study of geology.

Given the importance of water and its multitude of applications, an abundance of measurements of its properties have been made since the early twentieth century. A description of the entire continuum of the thermodynamic range of thermodynamic properties of water can be achieved with an equation of state capable of representing all available data (Rojas, 2013). Since 1970, the International Association for the Properties of Steam (IAPS) has been responsible for coordinating international investigations into the thermodynamic properties of water. IAPS in 1989 changed its name to the International Association for the Properties of Water and Steam (IAPWS), which is responsible for the international standardization of the thermophysical properties of water. These standardizations are published periodically. One of the most important is the equation of state for the thermodynamic properties of ordinary water for general and scientific use, IAPWS-95. In section 2 of this article we give a brief description of this formulation. Wagner and Pruss (2002) give a detailed study of this formulation.

2. IAPWS-95 FORMULATION FOR THE THERMODYNAMIC PROPERTIES OF ORDINARY WATER SUBSTANCE FOR GENERAL AND SCIENTIFIC USE

The algorithms we programmed using Wolfram Mathematica software (Wolfram, 2013) are based on IAPWS-95 formulation, which provides the most accurate thermodynamic properties of water in its fluid phase. It is a specific fundamental equation of the

Helmholtz free energy as a function of temperature and density, $f = f\,(T, \rho)$ and, consists of two parts; an ideal gas part ϕ^o and a residual part ϕ^r. It has the dimensionless form $\phi = f / RT$:

$$\frac{f(\rho, T)}{RT} = \phi\left(\delta, \tau\right) = \phi^o\left(\delta, \tau\right) + \phi^r(\delta, \tau) \tag{1}$$

The corresponding dimensionless expressions for the ideal gas parts φ^o and for the residual part φ^r of the Helmholtz free energy are given by equations (2) and (3):

$$\phi^o\left(\delta, \tau\right) = \ln\delta + n_1^o + n_2^o\tau + n_3^o \ln\tau + \sum_{i=4}^{8} n_i^o \ln\left[1 - e^{-\gamma_i^o}\right] \tag{2}$$

$$\phi^r\left(\delta, \tau\right) = \sum_{i=1}^{7} n_i \delta^{d_i} \tau^{t_i} + \sum_{i=8}^{51} n_i \delta^{d_i} \tau^{t_i} e^{-\delta^{c_i}} + \sum_{i=52}^{54} n_i \delta^{d_i} \tau^{t_i} e^{-\alpha_i(\delta-\varepsilon_i)^2 - \beta_i(\tau-\gamma_i)^2} + \sum_{i=55}^{56} n_i \Delta^{b_i} \delta \Psi \tag{3}$$

The definitions of ρ, T, δ and τ are in the nomenclature, section 6. The coefficients and parameters contained in Equations (2) and (3) are given by Wagner and Pruss (2002) and IAPWS (2009). The value of the gas constant is $R = 0.461\,518\,05$ kJ kg^{-1} K^{-1}.

Other thermodynamic properties are obtained by differentiation and algebraic manipulation of this Helmholtz potential without the use of any other information. All thermodynamic properties can be derived from Eq. (1) using the appropriate combinations of the dimensionless Helmholtz free energy and its derivatives as shown in Table 1.

Table 1. Relationships between the thermodynamic properties of water with the Helmholtz potential under the IAPWS-95 formulation. The partial derivatives of φ^o and φ^r can be found in the papers given by IAPWS (2009), Wagner and Pruss (2002) and Rojas (2013).

Thermodynamic Function	Relationship whit the Helmholtz Potential	Structure under IAPWS-95 Formulation
Pressure	$p = \rho^2\left(\frac{\partial f}{\partial \rho}\right)_T$	$\frac{p(\delta,\tau)}{\rho RT} = 1 + \delta\phi_\delta^r$
Entropy	$s = -\left(\frac{\partial f}{\partial T}\right)_\rho$	$\frac{s(\delta,\tau)}{R} = \tau\left(\phi_\tau^o + \phi_\tau^r\right) - \phi^o - \phi^r$
Internal Energy	$u = f - T\left(\frac{\partial f}{\partial T}\right)_\rho$	$\frac{u(\delta,\tau)}{RT} = \tau(\phi_\tau^o + \phi_\tau^r)$
Enthalpy	$h = f - T\left(\frac{\partial f}{\partial T}\right)_\rho + \rho\left(\frac{\partial f}{\partial \rho}\right)_T$	$\frac{h(\delta,\tau)}{RT} = 1 + \tau(\phi_\tau^o + \phi_\tau^r) + \delta\phi_\delta^r$
Isochoric Heat Capacity	$c_p = \left(\frac{\partial u}{\partial T}\right)_\rho$	$\frac{c_v(\delta,\tau)}{R} = -\tau^2(\phi_{\tau\tau}^o + \phi_{\tau\tau}^r)$
Isobaric Heat Capacity	$c_p = \left(\frac{\partial h}{\partial T}\right)_p$	$\frac{c_p(\delta,\tau)}{R} = -\tau^2\left(\phi_{\tau\tau}^o + \phi_{\tau\tau}^r\right) + \frac{(1 + \delta\phi_\delta^r - \delta\tau\phi_{\delta\tau}^r)^2}{1 + 2\delta\phi_\delta^r + \delta^2\phi_{\delta\delta}^r}$

$$\phi_\delta^r = \frac{\partial\phi^r}{\partial\delta},\ \phi_\tau^r = \frac{\partial\phi^r}{\partial\tau},\ \phi_\tau^o = \frac{\partial\phi^o}{\partial\tau},\ \phi_{\delta\tau}^r = \frac{\partial\phi^r}{\partial\delta\tau},\ \phi_{\delta\delta}^r = \frac{\partial\phi^r}{\partial\delta\delta},\ \phi_{\tau\tau}^r = \frac{\partial\phi^r}{\partial\tau\tau},\ \phi_{\tau\tau}^o = \frac{\partial\phi^o}{\partial\tau\tau}$$

ρ, T, δ, and τ as given in the nomenclature, Section 6. The value of the gas constant R is given in Section 5, Basic Constants of Water. The partial derivatives of the gas part and residual part are available in IAPWS (2009), and Wagner and Pruss (2002). Figures 1-6 shown 2D and 3D graphs of some of the thermophysical properties of water mentioned in Table 1; those graphs are for critical and supercritical water. All those graphs were obtained with the algorithms we programmed in Wolfram Mathematica sotware for the thermodynamic properties of water under the IAPWS-95 formulation.

The correlation for calculating the dynamic viscosity of H_2O (either in liquid, vapor, or supercritical-phase) is given by equation (4)

$$\overline{\mu} = \overline{\mu}_0\left(\theta\right) \times \overline{\mu}_1(\theta, \delta) \times \overline{\mu}_2(\theta, \delta) \tag{4}$$

The factors $\overline{\mu}_0$ y $\overline{\mu}_1$ are given by equations (5) and (6)

$$\bar{\mu}_0(\theta) = \frac{100\sqrt{\theta}}{\sum_{i=0}^{3} \frac{H_i}{\theta_i}} \tag{5}$$

$$\bar{\mu}_1(\theta,\delta) = \exp\left[\delta \sum_{i=0}^{5} \left(\frac{1}{\theta} - 1\right)^i \sum_{j=0}^{6} H_{ij} (\delta - 1)^j\right] \tag{6}$$

For definitions of θ and δ, see nomenclature. The values of the coefficients H_i and H_{ij} can be found in Huber *et al*. (2009), and IAPWS (2008). The term $\bar{\mu}_2$ is significant only over a range of temperatures and densities around the critical point. Away from this small critical region it contributes little in Eq. (4); for this reason, the computational speed and complexity is simplified setting $\bar{\mu}_2 = 1$, (Huber *et al*., 2009). The graphs of Figure 6 show the viscosity of H_2O in critical and supercritical thermodynamic conditions.

2.1 Saturation Properties

The correlations in this section allow us to calculate the thermodynamic properties of water at saturation.

The expression to calculate the vapor pressure p_σ has the form:

$$\log \frac{p_\sigma}{p_c} = \frac{T_c}{T}\left(a_1\vartheta + a_2\vartheta^{1.5} + a_3\vartheta^{3} + a_4\vartheta^{3.5} + a_5\vartheta^{4} + a_6\vartheta^{7.5}\right) \tag{7}$$

To calculate the densities of the saturated liquid ρ_l and the saturated vapor ρ_v we have the expressions:

$$\frac{\rho_l}{\rho_c} = 1 + b_1\vartheta^{1/3} + b_2\vartheta^{2/3} + b_3\vartheta^{5/3} + b_4\vartheta^{16/3} + b_5\vartheta^{43/3} + +b_6\vartheta^{110/3} \tag{8}$$

$$\log\left(\frac{\rho_v}{\rho_c}\right) = c_1\vartheta^{2/6} + c_2\vartheta^{4/6} + c_3\vartheta^{8/6} + c_4\vartheta^{18/6} + c_5\vartheta^{37/6} + c_6\vartheta^{71/6} \tag{9}$$

The equations to calculate the values of the specific enthalpy h, the specific internal energy u, and specific entropy s of the saturated liquid and the saturated vapor, are summarized as follows:

Specific enthalpy of the saturated liquid h_l and specific enthalpy of the saturated vapor h_v

$$h_l = \alpha + \frac{T}{\rho_l}\frac{dp_\sigma}{dT}, \qquad h_v = \alpha + \frac{T}{\rho_v}\frac{dp_\sigma}{dT} \tag{10}$$

Specific internal energy of the saturated liquid u_l and specific internal energy of the saturated vapor u_v

$$u_l = \alpha + \frac{1}{\rho_l}\left(T\frac{dp_\sigma}{dT} - p_\sigma\right), \qquad u_v = \alpha + \frac{1}{\rho_v}\left(T\frac{dp_\sigma}{dT} - p_\sigma\right) \tag{11}$$

Specific entropy of the saturated liquid s_l and specific entropy of the saturated vapor s_v

$$s_l = \psi + \frac{1}{\rho_l}\frac{dp_\sigma}{dT}, \qquad s_v = \psi + \frac{1}{\rho_v}\frac{dp_\sigma}{dT} \tag{12}$$

with ϑ as in the nomenclature. The numerical values for the critical parameters T_c, ρ_c, and p_c are identical to those given in section 5, Basic Constants of Water. The coefficients a_i, b_i, c_i, and the definitions of functions α and ψ can be found in the papers of Wagner and Pruss (1993) and IAPWS (1992a).

Based on equations (7) - (12), we programmed a module to calculate the thermodynamic saturation properties of water. The graphs of Figures 7-10 illustrate some of the results obtained with the algorithms for the saturation properties of water.

2.2 Range of Validity

The saturation properties are calculated for a temperature given from the triple point to the critical point. This corresponds to $273.16\ \mathrm{K} \le T \le 647.096\ \mathrm{K}$ ([0.01°C,373.942°C]). Based on extensive testing (IAPWS, 2009), the validity of the IAPWS-95 formulation is accepted in the entire region of stable fluid water from temperatures on the melting pressure curve up to 1273 K (1000°C), and pressures up to 1000 MPa (100 bar). Within this region, the IAPWS-95 formulation represents the experimental data available when IAPWS-95 was published (2009). Outside these limits, the formulation can be extrapolated to extremely high pressures and temperatures, acting reasonably to pressures up to 100 GPa (10^6 bar) and temperatures up to 5000 K (4727°C). For a more detailed description of the valid range around the critical point, for pressures and temperatures below the triple point, temperatures below 0°C, and the metastable regions, refer Wagner and Pruss (2002) and IAPWS (2009). The melting and sublimations pressure curves are described by the relations given by IAPWS (2011).

The numerical results displayed by the code we programmed in Wolfram Mathematica were exhaustively verified with the tables provide by Wagner and Pruss (2002; 1993), Huber *et al*. (2009), with the values that IAPWS (2009; 2008; 1994; 1992b) provides in their publications to assist programming its formulations on computers, and with the NIST/ASME Steam program: Database 10, Version 2.2, (Harvey *et al*., 1996). We extrapolated the algorithms to temperatures above 4000 K (3727°C).

3. PROTERMA. SOFTWARE AND COMPUTER CODE

The functional relationships presented in the previous sections are the most accurate representations that exist to determine the thermodynamic properties of water in a wide thermodynamic range. These relationships were the basis for the creation of the computer code ProTermA (In Spanish: *Propiedades Termodinámicas del Agua*, Thermodynamics Properties of Water) that we have developed in the Wolfram Mathematica programming language, with which we can reproduce the values of existing experimental measurements of thermodynamic properties of water in its fluid state (liquid, vapor, biphasic, supercritical) and visualize it in 2D and 3D graphics in an interactive way. In addition, the thermodynamic properties of water can be extrapolated to extreme thermodynamic conditions.

ProTermA is presented in an interactive graphical user interface. We present briefly the interface developed. Some of the results obtained with our programmed algorithms are shown in Figures 1-10. Figure 11 (left) shows the welcome screen, presenting the properties that can be calculated with the program. Figure 11 (right, top) shows options to choose from for the region in which we want to calculate the thermophysical properties of water. Figures 11 (right, bottom) is an example of the data entry screens. Figure 12 shows how the results are presented to the user on the screen.

One of the possibilities of the graphical interface we developed is the ability to display the properties of H_2O in 2D and 3D graphs. The interface for 3D graphics is as shown in Figure 13, we can chose the properties we want to display, we can change the background color, we can enlarge or shrink the chart, rotate it to have different visual perspectives, choose the range of graphing, and animate the graph, among other things. In the menu we can choose the chart to suit our needs, and instantly display it (Figure 14).

Another diverse application of the interface is to know how some property behaves in a specific isotherm or comparing behavior over a range of isotherms (Figure 15). We can also choose the thermophysical property that we need to see, instantly change it to analyze another isotherm, and more.

Not only can we analyze the properties of the liquid, vapor or supercritical water, but we also developed an interface that allows us to display the thermodynamic properties of biphasic water. It includes diverse options such as displaying on the same graph saturated properties of vapor and liquid, (Figure 16).

4. CONCLUSIONS

The general nature of the algorithms allows us to apply it to both low-temperature (isothermal) and variable-temperature geothermal systems.

The broad spectrum of thermodynamic validity of the algorithms allows the code to be used on any system that involves water in any of its phases in fluid: liquid, steam, two-phase, and supercritical water.

Programmed algorithms not only accurately reproduce existing measurements values, they also describe with great accuracy the thermodynamic behavior of supercritical water.

It is a powerful and useful tool in practical and theoretical exploration of geothermal resources.

It is an original program that provides a valuable teaching tool for anyone wishing to learn the thermodynamic properties of water.

The IAPWS-95 formulation could be updated with new experimental data, with the adoption of a new temperature scale, for example. But IAPWS expects that its formulations remain valid after applying these updates. Updating the code in the same way it would remain valid presenting the advantages already mentioned.

Geothermal energy is a virtually infinite renewable resource distributed more evenly over the planet than any other source of energy. Geothermal energy will be no longer available the day when the Earth comes to an end.

5. BASIC CONSTANTS OF WATER

In this section we list the numerical values of some thermodynamic constants of water, which are used throughout this text, and are also accepted and recommended by IAPWS (2001, 1992a) for calculating the thermodynamic properties of water with IAPWS-95 formulation.

Constants at the critical point of water	Constants at the triple point of water
$T_c = 647.096$ K	$T_t = 273.16$ K
$p_c = 22.064$ MPa	$p_t = 611.657$ Pa
$\rho_c = 322$ kg m^{-3}	$\rho_{lt} = 999.793$ kg m^{-3}
$\mu_c = 1.00 \times 10^{-6}$ Pa s	$\rho_{vt} = 0.004\,854$ kg m^{-3}

T_c, p_c, ρ_c, and μ_c are, respectively: temperature, pressure, density and viscosity of water at the critical point. T_t, p_t, ρ_{vt} and ρ_{lt} are, respectively: temperature, pressure, density of the saturated liquid and density of the saturated vapor at the triple point of H_2O. The gas constant for pure water has a value of $R = 0.461\,518\,05$ kJ kg^{-1} K^{-1}.

6. NOMENCLATURE

Thermodynamics quantities

c_p – Specific isobaric heat capacity.
c_v – Specific isochoric heat capacity.
f - Specific Helmholtz free energy.
h – Specific enthalpy.
p - Pressure.
R – Specific gas constant.
s – Specific entropy.
T – Absolute temperature.
u – Specific internal energy.
μ - Viscosity.
ρ – Mass density.
σ – Surface tension.

Dimensionless variables

δ – Reduce density, $\delta = \rho/\rho_c$.
θ – Reduce temperature, $\theta = T/T_c$.
ϑ – Auxiliary variable, $\vartheta = 1-\theta$.
$\overline{\mu}$ - Reduce viscosity, $\overline{\mu} = \mu / \mu_c$.
π – Reduce pressure, $\pi = p/p_c$.
τ – Reduce inverse temperature, $\tau = T_c/T$.
ϕ - Adimensioless Helmholtz free energy, $\phi = f/RT$.

The values of ρ_c, T_c, μ_c, P_c, and R are given in section 5.

Subscripts

c – Critical point.
t – Triple point.
σ - Saturation.
l – Saturated liquid state.
v – Saturated vapor state.

Superscripts

o – Ideal gas property.
r - Residual.

7. GRAPHICS AND FIGURES

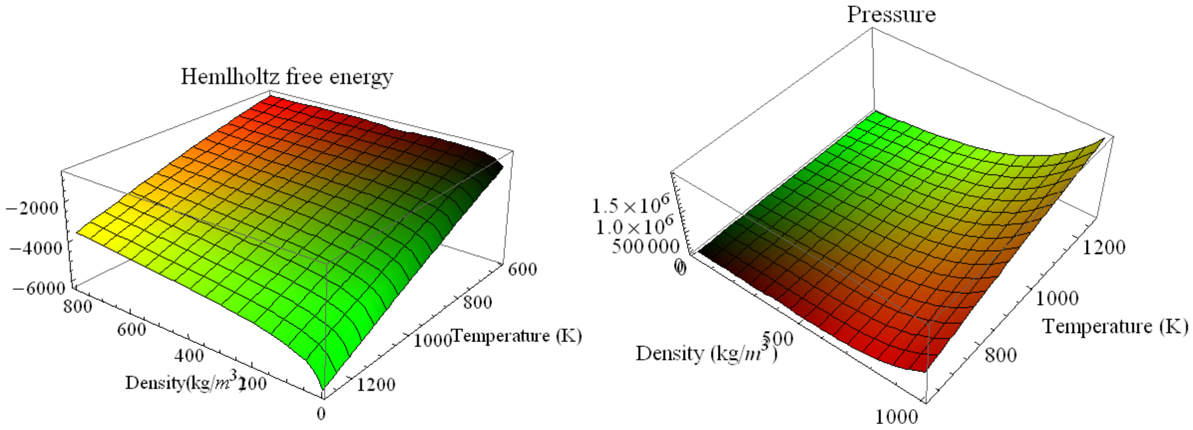


Figure 1: Left, Helmholtz surface in the critical and supercritical region of water as a function of density and temperature. Right, critical and supercritical pressure of water as a function of density and temperature.

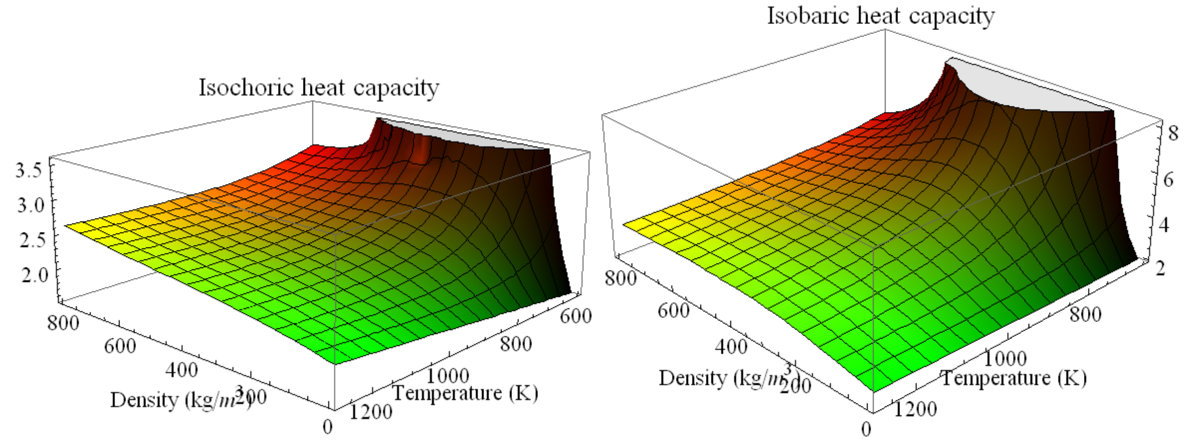


Figure 2. Left, isochoric heat capacity of critical and supercritical water as a function of density and temperature. Right, isobaric heat capacity of critical and supercritical water as a function of density and temperature.

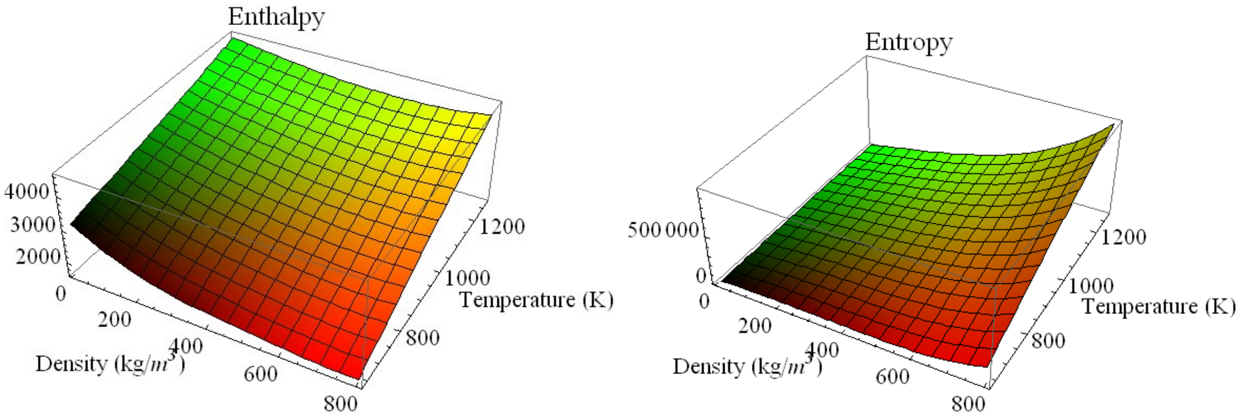


Figure 3. Specific enthalpy and specific entropy of water at the critical and supercritical region as a function of density and temperature.

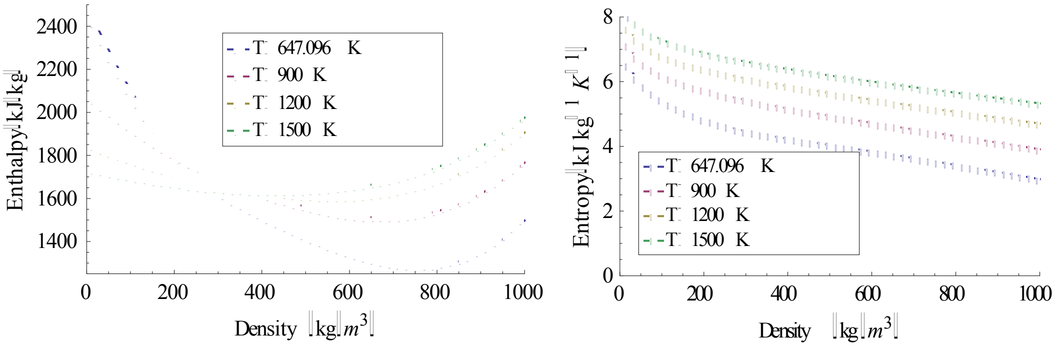


Figure 4. Specific enthalpy and entropy of water in terms of the density for various supercritical isotherms.

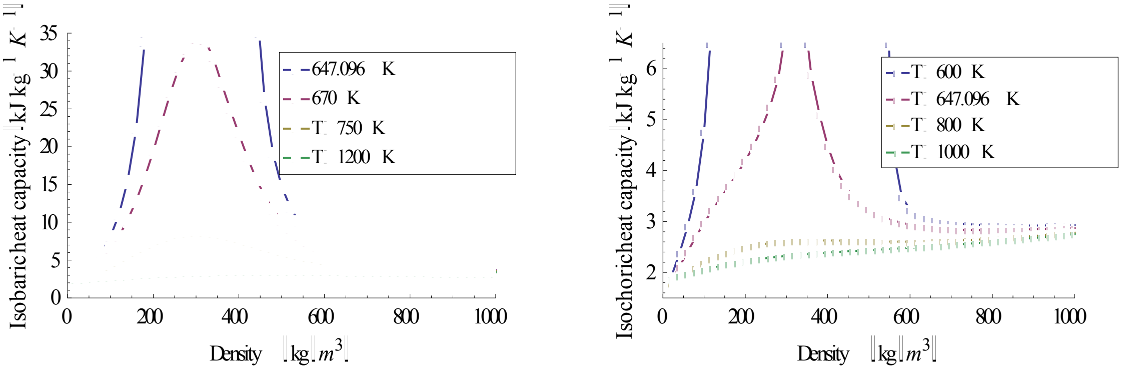


Figure 5. Specific isobaric and isochoric heat capacity of water as a function of density for different supercritical isotherms.

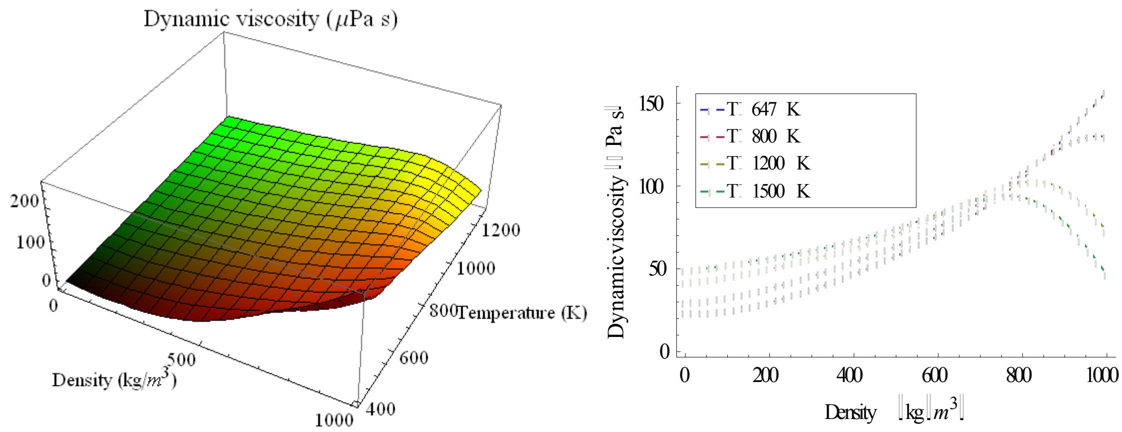


Figure 6. Left, dynamic viscosity graphic of water in critical conditions as a function of density and temperature. Right, dynamic viscosity of water as a function of density for various supercritical isotherms.

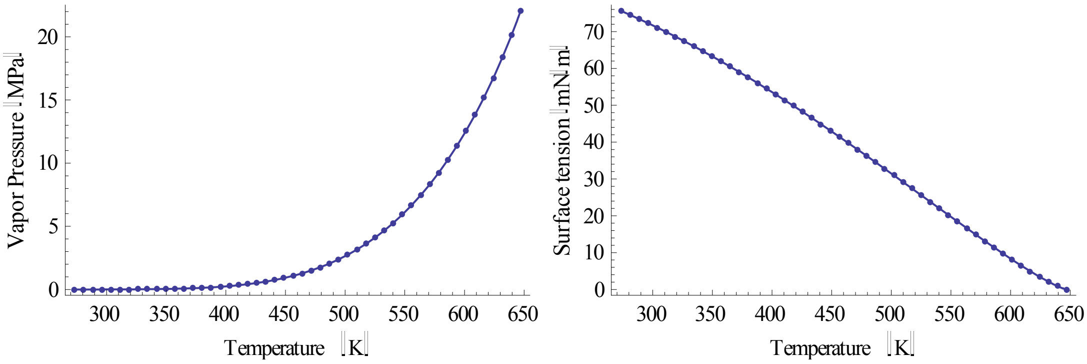


Figure 7. Left, vapor pressure of water in function of temperature. Right, surface tension for biphasic water as a function of temperature.

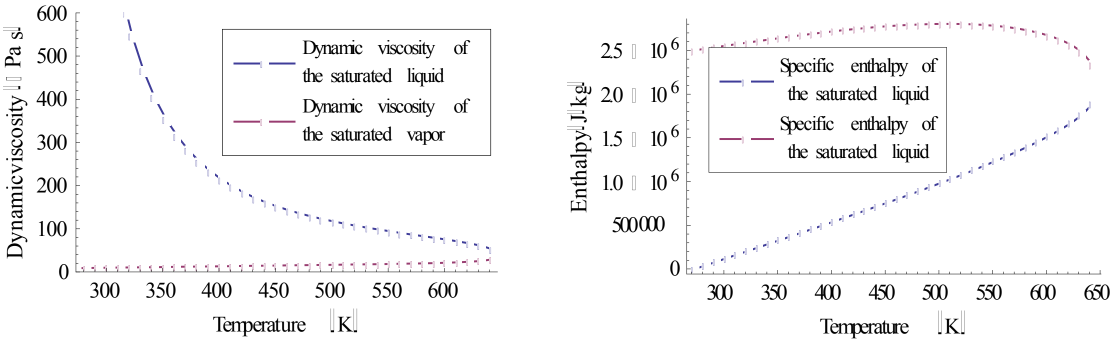


Figure 8. Left, dynamic viscosity of the saturated liquid and saturated vapor according to its saturation temperature. Right, density of the saturated liquid and saturated vapor depending on the saturation temperature.

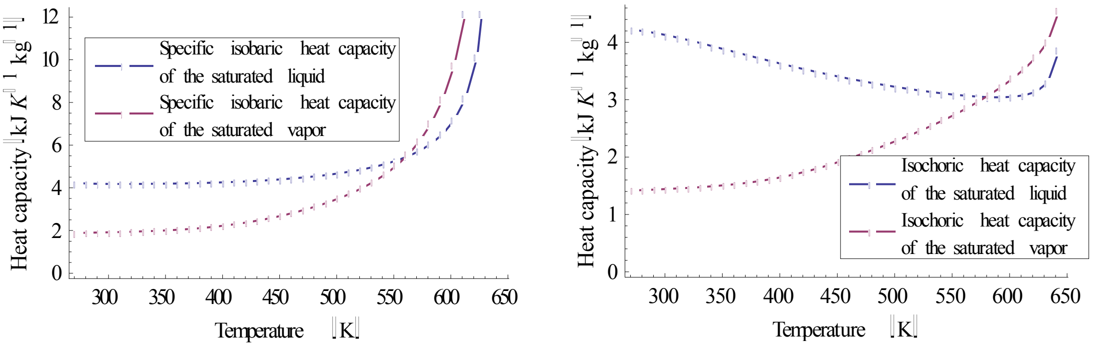


Figure 9. Left, specific isobaric heat capacity of the saturated liquid and saturated vapor in function of temperature. Right, specific isochoric heat capacity of the saturated liquid and saturated vapor as a function of its saturation temperature.

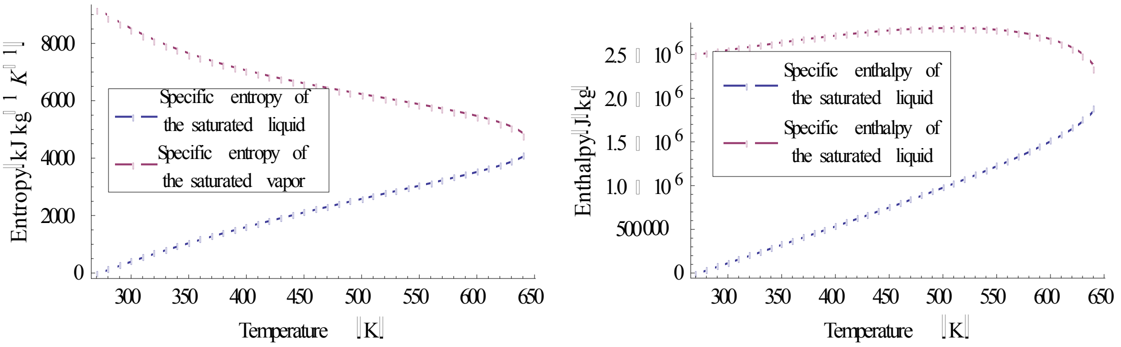
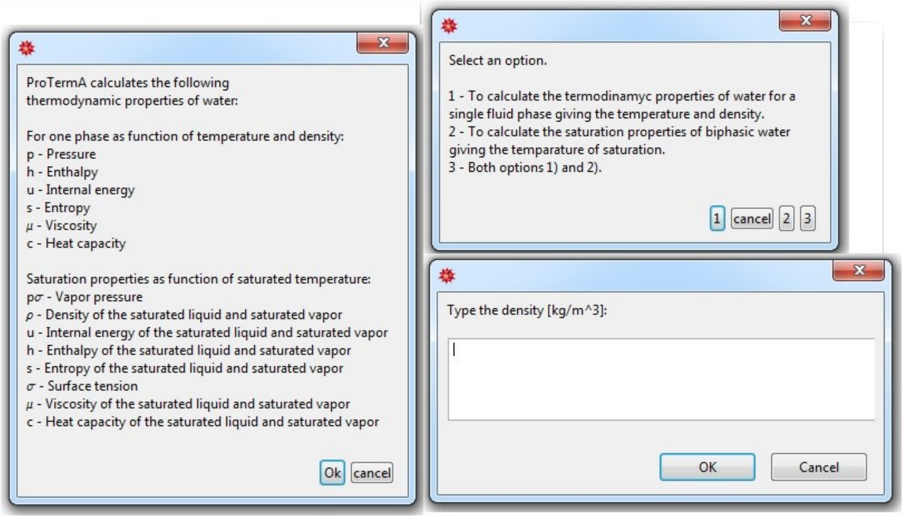


Figure 10. Specific saturated entropy (left) for two-phase water based on its saturation temperature. Specific saturated enthalpy (right) of biphasic water as a function of saturated temperature.



ProTermA calculates the following
thermodynamic properties of water:

For one phase as function of temperature and density:
p - Pressure
h - Enthalpy
u - Internal energy
s - Entropy
μ - Viscosity
c - Heat capacity

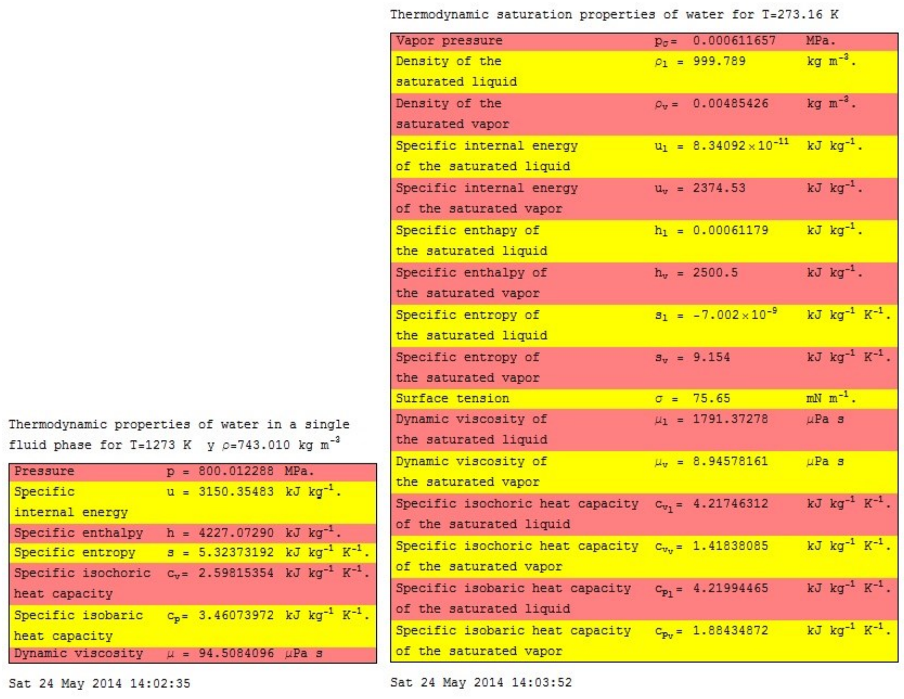
Saturation properties as function of saturated temperature:
$p\sigma$ - Vapor pressure
ρ - Density of the saturated liquid and saturated vapor
u - Internal energy of the saturated liquid and saturated vapor
h - Enthalpy of the saturated liquid and saturated vapor
s - Entropy of the saturated liquid and saturated vapor
σ - Surface tension
μ - Viscosity of the saturated liquid and saturated vapor
c - Heat capacity of the saturated liquid and saturated vapor

Select an option.

1 - To calculate the termodinamyc properties of water for a single fluid phase giving the temperature and density.
2 - To calculate the saturation properties of biphasic water giving the temparature of saturation.
3 - Both options 1) and 2).

Type the density [kg/m^3]:

Figure 11. Left, welcome screen when you start the program interface. Upper right, window with options to perform a computational task. Lower right, example of window to enter a value in the program.



Thermodynamic properties of water in a single fluid phase for T=1273 K y ρ=743.010 kg m^{-3}

Pressure	$p = 800.012288$	MPa.
Specific internal energy	$u = 3150.35483$	kJ kg^{-1}.
Specific enthalpy	$h = 4227.07290$	kJ kg^{-1}.
Specific entropy	$s = 5.32373192$	kJ kg^{-1} K^{-1}.
Specific isochoric heat capacity	$c_v = 2.59815354$	kJ kg^{-1} K^{-1}.
Specific isobaric heat capacity	$c_p = 3.46073972$	kJ kg^{-1} K^{-1}.
Dynamic viscosity	$\mu = 94.5084096$	μPa s

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Thermodynamic saturation properties of water for T=273.16 K

Vapor pressure	$p_\sigma = 0.000611657$	MPa.
Density of the saturated liquid	$\rho_l = 999.789$	kg m^{-3}.
Density of the saturated vapor	$\rho_v = 0.00485426$	kg m^{-3}.
Specific internal energy of the saturated liquid	$u_l = 8.34092 \times 10^{-11}$	kJ kg^{-1}.
Specific internal energy of the saturated vapor	$u_v = 2374.53$	kJ kg^{-1}.
Specific enthapy of the saturated liquid	$h_l = 0.00061179$	kJ kg^{-1}.
Specific enthalpy of the saturated vapor	$h_v = 2500.5$	kJ kg^{-1}.
Specific entropy of the saturated liquid	$s_l = -7.002 \times 10^{-9}$	kJ kg^{-1} K^{-1}.
Specific entropy of the saturated vapor	$s_v = 9.154$	kJ kg^{-1} K^{-1}.
Surface tension	$\sigma = 75.65$	mN m^{-1}.
Dynamic viscosity of the saturated liquid	$\mu_l = 1791.37278$	μPa s
Dynamic viscosity of the saturated vapor	$\mu_v = 8.94578161$	μPa s
Specific isochoric heat capacity of the saturated liquid	$c_{v_l} = 4.21746312$	kJ kg^{-1} K^{-1}.
Specific isochoric heat capacity of the saturated vapor	$c_{v_v} = 1.41838085$	kJ kg^{-1} K^{-1}.
Specific isobaric heat capacity of the saturated liquid	$c_{p_l} = 4.21994465$	kJ kg^{-1} K^{-1}.
Specific isobaric heat capacity of the saturated vapor	$c_{p_v} = 1.88434872$	kJ kg^{-1} K^{-1}.

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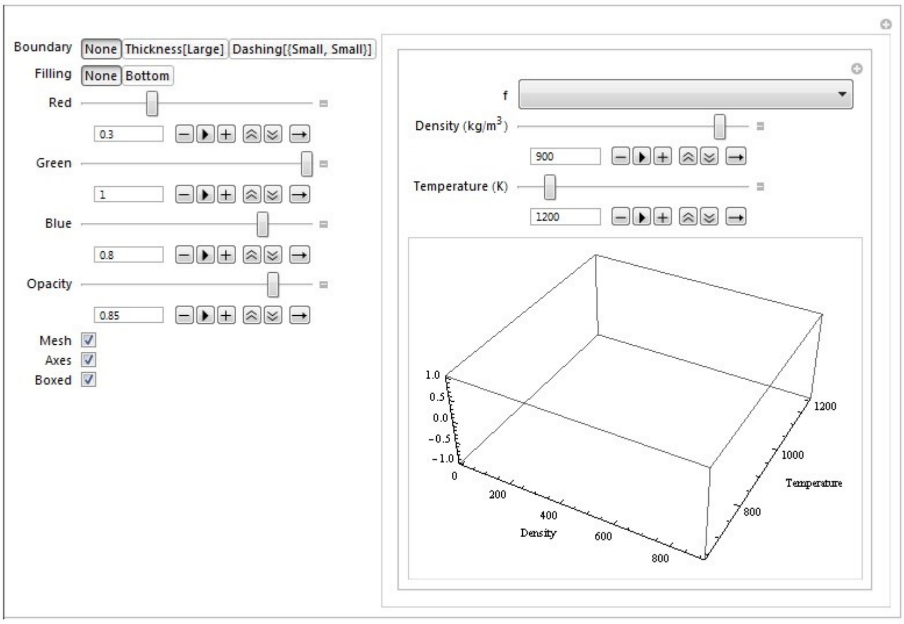
Figure 12. Left, example of how the thermodynamic properties are shown for one phase of water. Right, example for displaying the thermodynamic properties of biphasic water.



Red 0.3

Green 1

Blue 0.8

Opacity 0.85

Mesh ☑

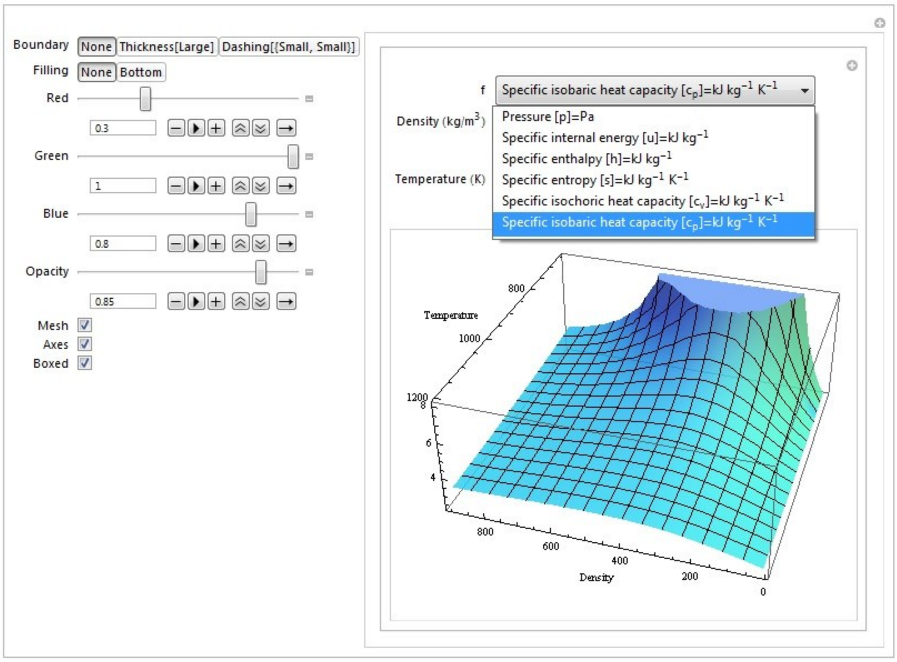
Axes ☑

Boxed ☑

Density (kg/m^3) 900

Temperature (K) 1200

Figure 13. Home screen with options for handling 3D graphics and presentation of the thermodynamic properties of supercritical water.



Red 0.3

Green 1

Blue 0.8

Opacity 0.85

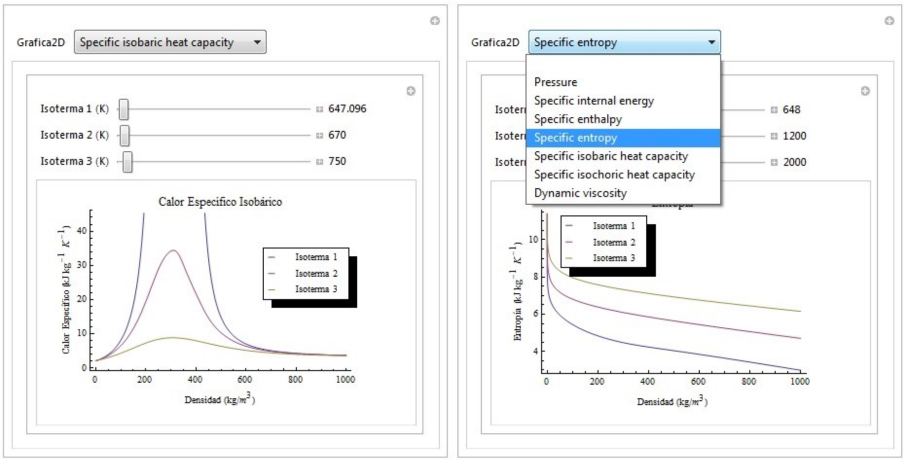
Mesh ☑

Axes ☑

Boxed ☑

f: Specific isobaric heat capacity [c_p]=kJ kg^{-1} K^{-1}

Figure 14. Tab down menus for choosing the thermodynamic property that is of interest to the user and manipulate it with the options presented in the interactive interface developed.



Grafica2D: Specific isobaric heat capacity

Isoterma 1 (K): 647.096

Isoterma 2 (K): 670

Isoterma 3 (K): 750

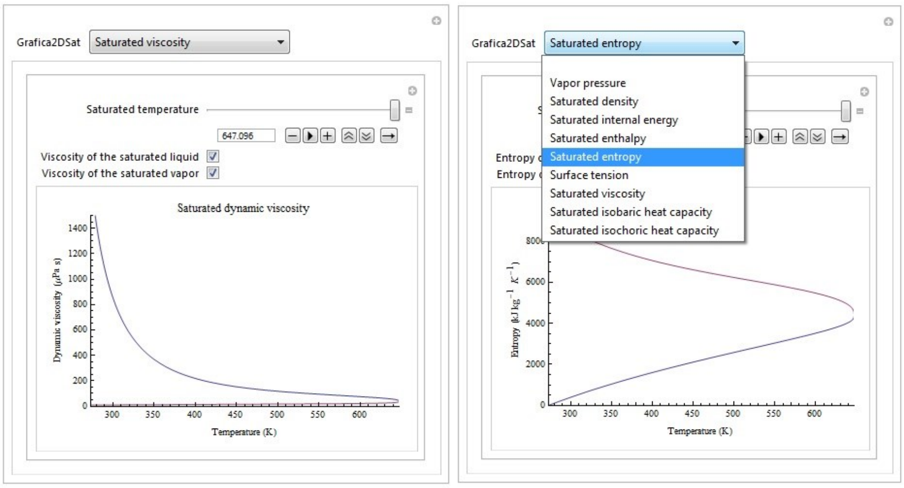
Grafica2D: Specific entropy

Isoterma 1 (K): 648

Isoterma 2 (K): 1200

Isoterma 3 (K): 2000

Figure 15. Interface display for manipulating and comparing 2D graphs of the thermodynamic properties of water at different supercritical isotherms.



Grafica2DSat: Saturated viscosity

Saturated temperature: 647.096

Viscosity of the saturated liquid ☑

Viscosity of the saturated vapor ☑

Grafica2DSat: Saturated entropy

Figure 16. Interface for manipulation, display and presentation of the different saturated thermodynamic properties of the liquid and steam of biphasic water as a function of its saturation temperature.

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