

# Steam Tables DLL

## Developer's Guide 1.1.0

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## 1. Overview

Properties of water is programmed in C#, based on the formulations given in References 1 through 4, which are called IAPWS-IF97, properties of water for industrial use.

The thermodynamic properties are given in 5 regions as shown in Figure 1. Region 4 is used only to calculate pressure or temperature along the saturation line. The other properties are calculated from the formulations in Regions 1, 2 or 3 at the saturation pressure and temperature.

Properties in Region 2 are calculated for stable steam, metastable states are not included.

As shown in Figure 1, properties are calculated as a function of pressure and density. Functions for the dependency of temperature corresponding to given pressure and density are also given in Reference 1.

The transport properties (thermal conductivity and viscosity) are calculated based on the formulations given in References 3 and 4. Since the transport properties are expressed in terms of temperature and density, calculation of density for given pressure and temperature is also needed in the computations. Therefore the transport properties are also not valid outside the regions shown in Figure 1. The terms in the viscosity and thermal conductivity formulations that improve the precision (see References 3 and 4) are not included. This implementation is also that used in the ASME Steam Tables for Industrial Use.

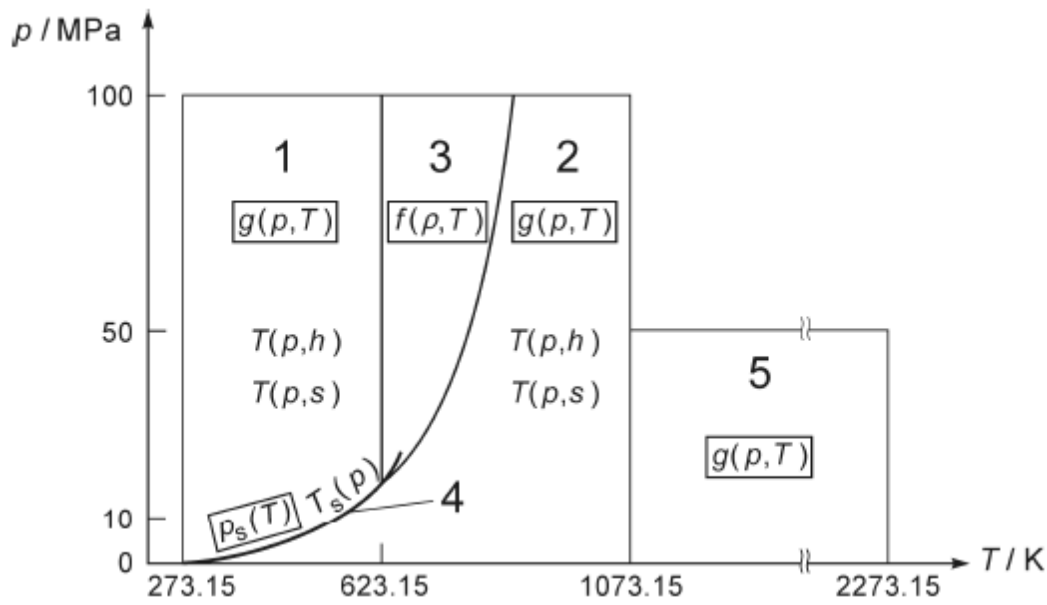


Figure 1. Regions of IAPWS-IF97 formulation (Reference 1)

## 2. The Structure of the Program

All of the classes are within the same namespace, “SteamProperties”. There is one class corresponding to each of Regions 1, 2, 3 and 5, in which all thermodynamic properties belonging to the respective region are calculated based on the Gibbs or Helmholtz function and their derivatives. The transport properties (viscosity and thermal conductivity) are calculated from the functions given in References 3 and 4. The transport property functions are much simpler and shorter as compared to the thermodynamic property functions.

The classes as listed below.

## **StmProp**

Contains the public functions for the properties. This class contains all of the interface functions of the DLL, hence an instance of this class must be created by the calling program (see User's Manual for examples). Also included in this class are functions for pressure as a function of temperature and temperature as a function of pressure along the saturation line, and along the boundary between regions 2 and 3. This class creates one instance of each of the following classes at initialization.

The interface routine are listed in the User's Manual and not repeated here.

## **REGION1**

Contains all thermodynamic property calculations in Region 1.

## **REGION2**

Contains all thermodynamic property calculations in Region 2.

## **REGION3**

Contains all thermodynamic property calculations in Region 3.

## **REGION5**

Contains all thermodynamic property calculations in Region 5.

## **TRANSPORT**

Contains transport property (thermal conductivity and viscosity) functions.

Although the formulation in IAPWS-IF97 does not require numerical iterations and hence much faster to compute than IAPWS-67, the property functions are lengthy in all regions and even lengthier in Region 3. It can be noticed that the same derivatives are used in computing multiple properties. To improve computation efficiency, the values of the derivatives are saved in each class from one call to the next. If the next call to the DLL is also for the same pressure and temperature value, the functions and their derivatives are not recalculated, rather, previously calculated values are used.

On entry into the public functions, the input values are checked for validity. If the input temperature or pressure is out of bounds, *stat* is set to 1 and *errorMessage* is set.

The calling program should not be using this package if its intended application range exceeds that in Figure 1. However, many programs may go through too high or too low pressure / temperature states

during the iterations although the converged solution is expected to be well within the range of application, and recover from it. In order to support calling programs that are not written with a good practice of error checking, the DLL always returns a reasonable number so that the calling program would not crash during the iterations. For this purpose, the properties are calculated at the closest valid point to the input when the inputs are out of bounds, and the calling program may continue with the iterations even when the nonzero return value of stat (error status) is ignored. However if the input to the steam tables is a NonNumber, a crash may still occur.

### 3. Class REGION1

REGION1 includes all raw properties within Region 1 shown in Figure 1. Region 1 includes subcooled liquid except a small section near critical power. The formulation is given in Reference 1.

The properties are calculated from the Gibbs function and its derivatives as a function of pressure and temperature. For example,

$$v = \left. \frac{\partial g}{\partial p} \right|_T$$

First, the Gibbs function, g and its derivatives as a function of reduced pressure and temperature are calculated from the polynomials given in Reference 1 as a function of pressure and temperature. The functions are,

**Table 3.1 Fundamental Functions in Region 1**

<code>double G1(double p, double t)</code>	$\gamma(\pi, \tau)$
<code>double G1_p(double p, double t)</code>	$\left. \frac{\partial \gamma(\pi, \tau)}{\partial \pi} \right _{\tau}$
<code>double G1_t(double p, double t)</code>	$\left. \frac{\partial \gamma(\pi, \tau)}{\partial \tau} \right _{\pi}$
<code>double G1_pp(double p, double t)</code>	$\left. \frac{\partial^2 \gamma(\pi, \tau)}{\partial \pi^2} \right _{\tau}$
<code>double G1_tt(double p, double t)</code>	$\left. \frac{\partial^2 \gamma(\pi, \tau)}{\partial \tau^2} \right _{\pi}$
<code>double G1_pt(double p, double t)</code>	$\frac{\partial^2 \gamma(\pi, \tau)}{\partial \tau \partial \pi}$

where  $\gamma(\pi, \tau) = \frac{g(p, T)}{RT}$ ,  $\pi = \frac{p}{p^*}$ ,  $\tau = \frac{T}{T^*}$ . The reference values (quantities with star superscript) are given in Reference 1.

In each of the functions, the reduced pressure, temperature and the calculated values of the Gibbs function and its derivatives are saved in `state` structure. For as long as the pressure and temperature values do not change, more elements of the `state` structure are filled each time one of the functions in the above table is called. When a function is called, the `state` structure is checked to find if this function has already been calculated for the same pressure and temperature.

- If the pressure or temperature is not the same as the pressure and temperature in the `state` structure, all elements of the `state` structure are initialized to `double.minValue`, and the calculations are performed and the new values are saved in the `state` structure.
- If the pressure and temperature are the same as in those in the `state` structure, but the value for this function is still `double.minValue`, the calculations are performed and the new values are saved in the `state` structure.
- If the pressure and temperature are the same as in those in the `state` structure, and the value for this function exists in `state` structure, no calculations are performed, the value in `state` structure is returned.

The following properties are calculated from the relationships given in Reference 1.

**Table 3.2. Public Functions in Region 1**

<code>public double V(double p, double t)</code>	$v(p, T) \frac{p}{RT}$
<code>public double H(double p, double t)</code>	$\frac{h(p, T)}{RT}$
<code>public double S(double p, double t)</code>	$\frac{s(p, T)}{R}$
<code>public double CP(double p, double t)</code>	$\frac{c_p(p, T)}{R}$
<code>public double CV(double p, double t)</code>	$\frac{c_v(p, T)}{R}$
<code>public double Tph(double p, double h)</code>	$T(p, h)$
<code>public double Tps(double p, double s)</code>	$T(p, s)$

## 4. Class REGION2

REGION2 includes all raw properties within Region 2 shown in Figure 1. Region 2 includes superheated steam except a small section near critical power. The formulation is given in Reference 1.

The structure of this class is similar to that of Class REGION1 in Section 3.

## 5. Class REGION3

REGION3 includes all raw properties within Region 3 shown in Figure 1. Region 3 properties are given as a function of temperature and density and derived from the Helmholtz function and its derivatives, also given as a function of temperature and density. The following are the functions to calculate the Helmholtz function and its derivatives.

**Table 5.1 Fundamental Functions in Region 3**

<code>double</code> Phi( <code>double</code> r, <code>double</code> t)	$\phi(\delta, \tau)$
<code>double</code> Phi_r( <code>double</code> r, <code>double</code> t)	$\left. \frac{\partial \phi(\delta, \tau)}{\partial \delta} \right _{\tau}$
<code>double</code> Phi_t( <code>double</code> r, <code>double</code> t)	$\left. \frac{\partial \phi(\delta, \tau)}{\partial \tau} \right _{\delta}$
<code>double</code> Phi_rr( <code>double</code> r, <code>double</code> t)	$\left. \frac{\partial^2 \phi(\delta, \tau)}{\partial \delta^2} \right _{\tau}$
<code>double</code> Phi_tt( <code>double</code> r, <code>double</code> t)	$\left. \frac{\partial^2 \phi(\delta, \tau)}{\partial \tau^2} \right _{\delta}$
<code>double</code> Phi_rt( <code>double</code> r, <code>double</code> t)	$\frac{\partial^2 \phi(\delta, \tau)}{\partial \tau \partial \delta}$

where  $\phi(\delta, \tau) = \frac{f(\rho, T)}{RT}$ ,  $\rho = \frac{\rho}{\rho^*}$ ,  $\tau = \frac{T}{T^*}$ . The reference values (quantities with star superscript)

are given in Reference 1. In each of the functions, the reduced density, temperature and the calculated values of the Helmholtz function and its derivatives are saved in `state` structure, similar to that in Region 1 (see Section 3). The following functions are used to compute the properties.

**Table 5.2 Property Functions in Region 3 as a function of density and temperature**

<code>double Hrt(double r, double t)</code>	$\frac{h(\rho, T)}{RT}$
<code>double Srt(double r, double t)</code>	$\frac{s(\rho, T)}{R}$
<code>double CPrt(double r, double t)</code>	$\frac{c_p(\rho, T)}{R}$
<code>double CVrt(double r, double t)</code>	$\frac{c_v(\rho, T)}{R}$

Properties as a function of pressure and temperature are calculated in the following functions. These functions first call `Rho` to get the density, and then call one of the functions with known density and temperature in the above table to calculate the property. Also temperature as a function of enthalpy or entropy are included.

**Table 5.3 Public Functions in Region 3**

<code>public double Prt(double r, double t)</code>	$p$ in kPa
<code>public double Rho(double p, double t, int phase)</code>	$\rho$ in kg/m <sup>3</sup> . See Section 5.1
<code>public double V(double p, double t)</code>	$v(p, T) \frac{p}{RT}$
<code>public double H(double p, double t)</code>	$\frac{h(p, T)}{RT}$
<code>public double S(double p, double t)</code>	$\frac{s(p, T)}{R}$
<code>public double CP(double p, double t)</code>	$\frac{c_p(p, T)}{R}$
<code>public double CV(double p, double t)</code>	$\frac{c_v(p, T)}{R}$
<code>public double Tph(double p, double h)</code>	$T(p, h)$
<code>public double Tps(double p, double s)</code>	$T(p, s)$

## 5.1 Calculating Density Given Pressure and Temperature in Region 3

Since in many practical cases, the pressure and temperature is known, rather than temperature and density, additional relationships are needed to find density as a function of pressure and temperature. The density given pressure and temperature is calculated in

```
public double Rho(double p, double t, int phase)
```

The formulation for specific volume as a function of pressure and temperature is given in Reference 2. The argument, `phase`, is only relevant for saturated cases, which will be explained in Section 5.2.

Region 3 is divided in many subregions, 3a, 3b, ... 3z. The subregion is determined in,

```
void SubRegion(double p, double t)
```

using the formulation in Reference 2. This function does not return a value, rather it sets,

```
state.SubRegion
```

Function `Rho` first checks if the density at the given pressure and temperature has already been calculated and the phase matches the existing value of phase in `state.phase`. If so, the density is not recalculated, rather the value in `state.SubRegion` is returned. If the density has not been calculated at this point yet, the subregion region is determined by calling `SubRegion` function, and specific volume is then calculated by calling the corresponding specific volume function for this subregion, which is one of `Vpt_3a`, `Vpt_3b`, ... , `Vpt_3z`, using the relationships given in Reference 2.

## 5.2 Saturated liquid or steam properties in Region 3

Region 3 also includes saturation line between 623.15 °K and critical temperature.

The saturated liquid density is calculated in `Rho` with argument `phase` set to 1, and with pressure and temperature values on the saturation line. `Rho` passes the argument `phase` to function `SubRegion`. If the subregion corresponding to the given pressure and temperature is one of the subregions adjacent to the saturation line, the subregion is set to the subregion for subcooled liquid even if it turns out to be that for saturated steam due to the small differences in pressure and temperature values. The properties are then calculated corresponding to the density and temperature for subcooled liquid.

Saturated steam properties are calculated similarly by setting the subregion to that corresponding to the superheated steam adjacent to the saturation line.

Checking `state.phase` in function `Rho` before determining whether or not the density should be recalculated or the previously calculated density should be returned ensures that incorrect properties



are not calculated, if for example the first call to `Rho` is for saturated liquid and the next call is for saturated steam at the same pressure and temperature.

## 6. Class REGION5

REGION5 includes all raw properties within Region 5 shown in Figure 1. Region 5 includes superheated steam at high temperature. The formulation is given in Reference 1.

The structure of this class is similar to that of Class REGION1 in Section 3. This region does not have temperature as a function of enthalpy or entropy in this version.

## 7. Determining the Region for given pressure and temperature

As shown in Figure 1, Regions 1 and 2 are separated by the saturation line below 623.15 °K, and by a constant temperature line above 623.15 °K. Regions 2 and 3 are separated by a more or less constant entropy line.

The region the state falls into given pressure and temperature is determined in function,

```
public int SubRegion(ref double p, ref double t)
```

This function is in class `StmProp`, sets the region in the `state` structure (see Section 0) and returns the region number.

### 7.1 Saturation Line (Region 4)

There are two functions for the pressure – temperature relationship in `StmProp` class:

- `double Pi_4 (double t)` is pressure as a function of temperature along the saturation line, from triple point to critical temperature.
- `double Theta_4 (double p)` is temperature as a function of pressure along the saturation line, from triple point to critical pressure.

Note that the triple point is slightly higher than 273.15 °K. The saturation temperature and pressure relationship can be extrapolated to 273.15 °K. However, the properties as implemented in this DLL are limited to temperatures at or above the triple point temperature of 273.16 °K.

Once the pressure and temperature are calculated from either `Pi_4` or `Theta_4`, the properties of saturated liquid is calculated from Region 1 equations, and the properties of saturated steam is calculated from Region 2 equations if the temperature is less than 623.15 °K (see Figure 1). For temperatures higher than 623.15 °K, both saturated liquid and saturated steam are calculated from Region 3 equations using the appropriate subregion. See Section 5.

## 7.2 Boundary Between Regions 2 and 3

There are two functions for the pressure – temperature relationship in `StmProp` class:

- `double P23(double t)` is pressure as a function of temperature along the boundary between Regions 2 and 3.
- `double T23(double p)` is temperature as a function of pressure along the boundary between Regions 2 and 3.

## 7.3 Structure state in Class `StmProp`

The state structure saves the pressure, temperature, quality and region at the last calculated point. This structure is public and the elements can be interrogated by the calling program to determine the quality and region of the last calculated state.

# 8. Temperature as function of pressure and enthalpy or entropy

Calculation of Temperature as a function of pressure and enthalpy or entropy are in Regions 1, 2 and 3, is described in this section.

Since the region boundaries are given in terms of pressure and temperature, it is necessary to develop an additional algorithm to first determine the region given pressure and enthalpy or entropy before calling the property functions in each region. This is accomplished in functions `Tph` and `Tps` in class `StmProp`.

## 8.1 Temperature as a function of pressure and enthalpy

Temperature, given pressure and enthalpy is calculated in function `Tph`. The algorithm to determine the region is described below.

If  $p < 16529.164$  kPa (this corresponds to 623.15 °K, see Figure 1)

First  $h_f(p)$  and  $h_g(p)$  are calculated.

If  $h < h_f(p)$ , temperature is calculated from Region 1 equations.

If  $h > h_g(p)$ , temperature is calculated from Region 2 equations.

If  $h_f(p) \leq h \leq h_g(p)$ , the temperature is the saturation temperature.

Quality is calculated from,

$$x = \frac{h - h_f}{h_g - h_f}$$

If  $16529.164 \text{ kPa} < p < p_c$  ( $p_c$  is critical pressure)

This can be in Regions 1, 2 or 3.

First the saturation enthalpy of liquid,  $h_f(p)$ , and steam,  $h_g(p)$ , are calculated from Region 3 equations. There are three possible cases as follows.

1. Saturated case

If  $h_f(p) \leq h \leq h_g(p)$ , this point is in Region 3. Temperature is the saturation temperature.

2. Subcooled liquid case

If  $h \leq h_f(p)$ , this point may be in Region 1 or Region 3. Region 1 boundary at constant  $T=623.15 \text{ °K}$  (see Figure 1) corresponds to the section in P-h plane after the blue dot in Figure 2. A curve fit to this boundary is as follows.

$$h_{1-3}(p) = 7.27071 \times 10^{-18} p^4 - 2.06464 \times 10^{-12} p^3 + 2.23637 \times 10^{-7} p^2 - 1.14480 \times 10^{-2} p + 1.80136 \times 10^3 \quad (1)$$

where P is in kPa, and h is in kJ/kg.

If  $h < h_{1-3}(p)$ , temperature is calculated from Region 1 equations,

If  $h > h_{1-3}(p)$ , temperature is calculated from Region 3 equations.

3. Superheated steam case

The temperature at the boundary of Regions 2 and 3 is calculated from T23 in Section 7.2. Corresponding enthalpy at the boundary,  $h_{2-3}(p)$  is calculated from Region 2 equations.

If  $h < h_{2-3}(p)$ , temperature is calculated from Region 2 equations,

If  $h > h_{2-3}(p)$ , temperature is calculated from Region 3 equations.

Quality is calculated from,

$$x = \frac{h - h_f}{h_g - h_f}$$

If  $p > p_c$  ( $p_c$  is critical pressure)

A curve is fit to Region 2 boundary in P-h plane was made in two sections,

For  $p < 40000$  kPa

$$h_{2-3}(p) = -1.53693 \times 10^{-15} p^4 + 1.99564 \times 10^{-10} p^3 - 9.49050 \times 10^{-6} p^2 + 1.94414 \times 10^{-1} p + 1.17743 \times 10^3 \quad (2)$$

For  $p > 40000$  kPa

$$h_{2-3}(p) = 8.04207 \times 10^{-18} p^4 - 2.67059 \times 10^{-12} p^3 + 3.33749 \times 10^{-7} p^2 - 1.46824 \times 10^{-2} p + 2.81053 \times 10^3 \quad (3)$$

where P is in kPa, and h is in kJ/kg. The curve fits are not very accurate as critical pressure is approached, but the error is less than 10 kJ/kg. One iteration is sufficient to determine the correct region as described below.

If  $h < h_{1-3}(p) + 10$ , temperature is calculated from Region 1 equations. 10 kJ/kg is added to account for uncertainties in Equation (1). The region is checked again by calling SubRegion(p,t). If region is 1, the calculated temperature is the correct temperature, and no further calculations are needed.

If region is not 1, temperature may be in regions 2 or 3. Boundary between regions 2 and 3,  $h_{2-3}(p)$ , is calculated from Equations (2) or (3), depending on the pressure.

If  $h > h_{2-3}(p) - 10$ , temperature is calculated from Region 2 equations. 10 kJ/kg is subtracted to account for uncertainties in Equations (2) and (3).

If  $h > h_{1-3}(p)$ , temperature is calculated from Region 3 equations. The region is checked again by calling SubRegion(p,t). If region is 2, the calculated temperature is the correct temperature, and no further calculations are needed. If region is not 2, the given (p,h) state is in Region 3, and temperature is calculated from Region 3 equations.

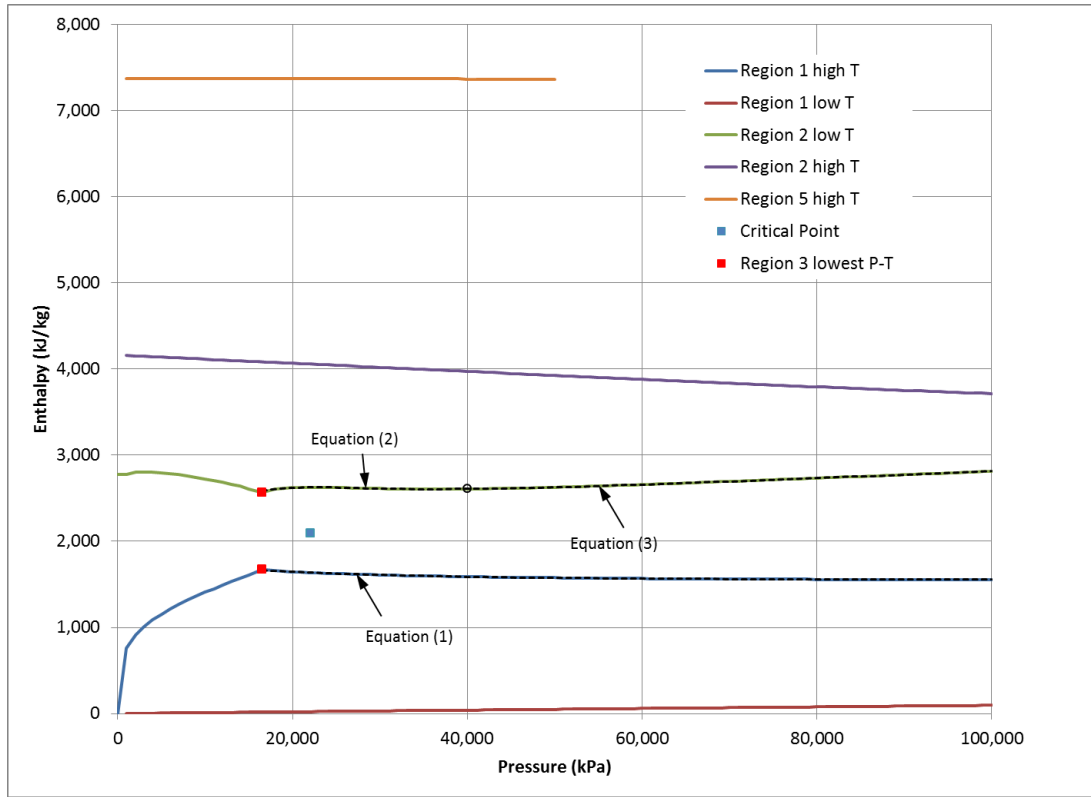


Figure 2. Region Boundaries in P-h Plane

## 8.2 Temperature calculation given pressure and entropy

Temperature, given pressure and entropy is calculated in function Tps. The algorithm to determine the region is described below. This is analogous to the calculation of temperature given pressure and enthalpy described in Section 8.2.

If  $p < 16529.164$  kPa (this corresponds to 623.15 °K, see Figure 1)

First  $s_f(p)$  and  $s_g(p)$  are calculated.

If  $s < s_f(p)$ , temperature is calculated from Region 1 equations.

If  $s > s_g(p)$ , temperature is calculated from Region 2 equations.

If  $s_f(p) \leq s \leq s_g(p)$ , the temperature is the saturation temperature.

Quality is calculated from,

$$x = \frac{s - s_f}{s_g - s_f}$$

If  $16529.164 \text{ kPa} < p < p_c$  ( $p_c$  is critical pressure)

This state can be in Regions 1, 2 or 3.

First the saturation entropy of liquid,  $s_f(p)$ , and steam,  $s_g(p)$ , are calculated from Region 3 equations. There are three possible cases as follows.

1. Saturated case

If  $s_f(p) \leq s \leq s_g(p)$ , this point is in Region 3. Temperature is the saturation temperature.

2. Subcooled liquid case

If  $s \leq s_f(p)$ , this point may be in Region 1 or Region 3. Region 1 boundary at constant  $T=623.15 \text{ °K}$  (see Figure 1) corresponds to the section in P-s plane after the blue dot in Figure 3. A curve fit to this boundary is as follows.

$$s = 3.76683 \times 10^{-11} p^2 - 8.36729 \times 10^{-6} p + 3.86940 \quad (1)$$

where P is in kPa, and s is in kJ/kg °K.

If  $s < s_{1-3}(p)$ , temperature is calculated from Region 1 equations,

If  $s > s_{1-3}(p)$ , temperature is calculated from Region 3 equations.

3. Superheated steam case

The temperature at the boundary of Regions 2 and 3 is calculated from T23 in Section 7. Corresponding entropy at the boundary,  $s_{2-3}(p)$  is calculated from Region 2 equations.

If  $s < s_{2-3}(p)$ , temperature is calculated from Region 2 equations,

If  $s > s_{2-3}(p)$ , temperature is calculated from Region 3 equations.

Quality is calculated from,

$$x = \frac{s - s_f}{s_g - s_f}$$

If  $p > p_c$  ( $p_c$  is critical pressure)

A curve is fit to Region 2 boundary in P-h plane was made in two sections,

For  $p < 40000$  kPa

$$s = -2.11798 \times 10^{-26} p^6 + 3.88682 \times 10^{-21} p^5 - 2.95203 \times 10^{-16} p^4 \\ 1.18836 \times 10^{-11} p^3 - 2.67319 \times 10^{-7} p^2 + 3.17149 \times 10^{-3} p - 1.01618 \times 10^1 \quad (2)$$

For  $p > 40000$  kPa

$$s = -2.96307 \times 10^{-25} p^5 + 1.17911 \times 10^{-19} p^4 \\ -1.89365 \times 10^{-14} p^3 + 1.54787 \times 10^{-9} p^2 - 6.35368 \times 10^{-5} p + 6.08131 \quad (3)$$

where P is in kPa, and s is in kJ/kg °K. The curve fits are not very accurate as critical pressure is approached, but the error is less than 0.05 kJ/kg °K. One iteration is sufficient to determine the correct region as described below.

If  $s < s_{1-3}(p) + 0.05$ , temperature is calculated from Region 1 equations. 0.05 kJ/kg °K is added to account for uncertainties in Equation (1). The region is checked again by calling SubRegion(p,t). If region is 1, the calculated temperature is the correct temperature, and no further calculations are needed.

If region is not 1, this state may be in regions 2 or 3. Boundary between regions 2 and 3,  $s_{2-3}(p)$ , is calculated from Equations (2) or (3), depending on the pressure.

If  $s > s_{2-3}(p) - 0.05$ , temperature is calculated from Region 2 equations. 0.05 kJ/kg °K is subtracted to account for uncertainties in Equations (2) and (3).

If  $h > h_{1-3}(p)$ , temperature is calculated from Region 3 equations. The region is checked again by calling SubRegion(p,t). If region is 2, the calculated temperature is the correct temperature, and no further calculations are needed. If region is not 2, the given (p,h) state is in Region 3, and temperature is calculated from Region 3 equations.

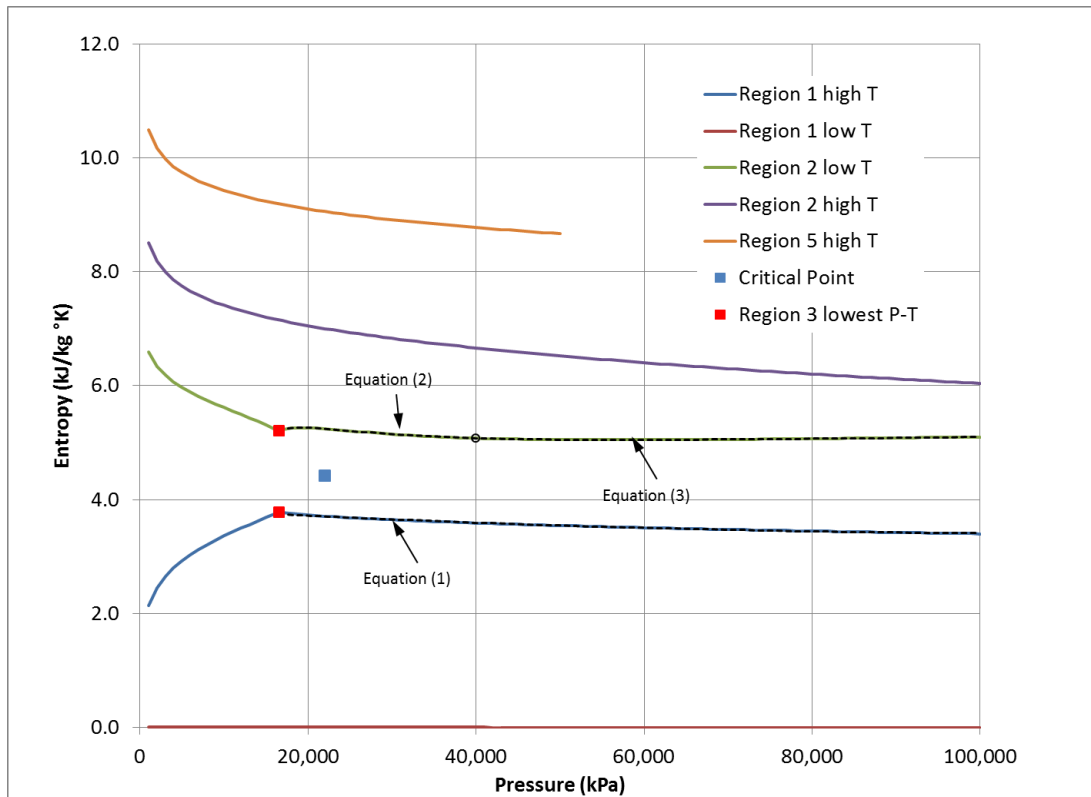


Figure 3. Region Boundaries in P-s Plane

## 9. References

1. "Revised Release on the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam," The International Association for the Properties of Water and Steam, August 2007 (can be obtained from <http://www.iapws.org>).
2. "Supplementary Release on Backward Equations for Specific Volume as a Function of Pressure and Temperature  $v(p,T)$  for Region 3 of the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam," The International Association for the Properties of Water and Steam, July 2005 (can be obtained from <http://www.iapws.org>).
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