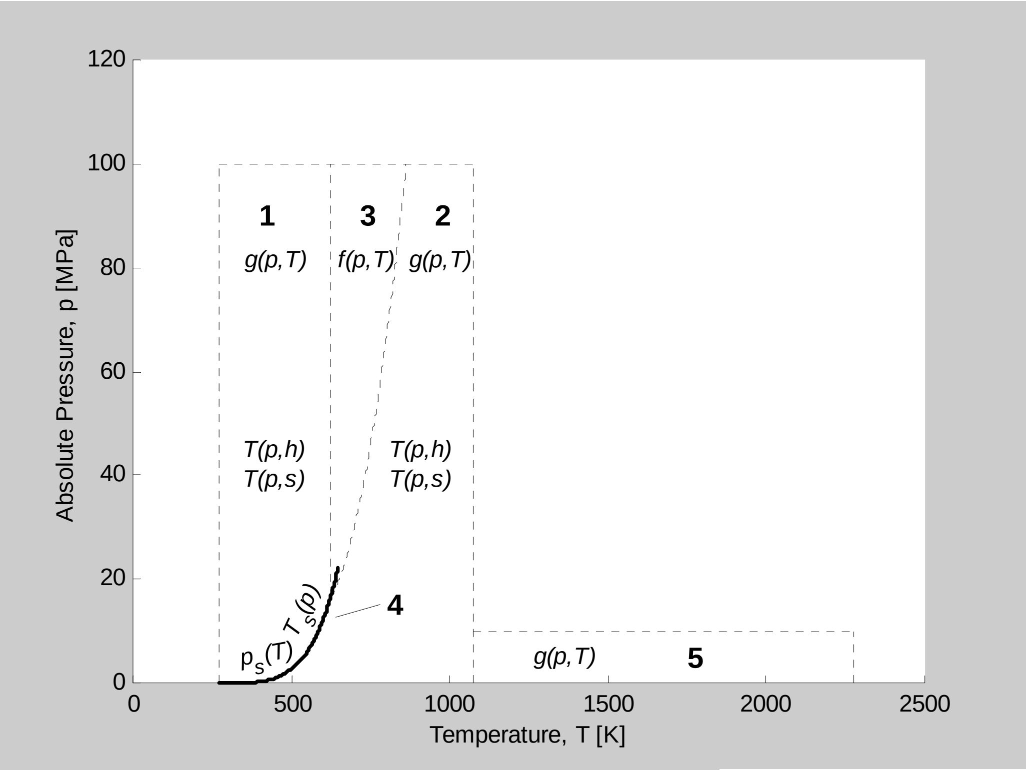
Water and Steam

Thermophysical Properties for MATLAB®



IAPWS-IF97

Specific Volume
Specific Internal Energy
Specific Entropy
Specific Enthalpy
Specific Heat Capacity
Speed of Sound
Isentropic Exponent

IAPWS

Viscosity
Thermal Conductivity
Surface Tension
Refractive index
Prandtl Number

User's Guide

KHACE

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Water and Steam Thermophysical Properties for MATLAB User's Guide.

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Introduction

IAPWS Thermodynamic and Transport Properties

In 1997, at a meeting of the International Association for the Properties of Water and Steam (IAPWS), a new formulation for the thermodynamic properties of water and steam was adopted as the new international standard. The name of the industrial standard is: "IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam"; also known as "IAPWS Industrial Formulation 1997" or "IAPWS-IF97", for short.

The IAPWS-IF97 standard defines equations for calculating the following thermodynamic properties as a function of temperature and pressure:

- Specific volume
- Specific internal energy
- Specific entropy
- Specific enthalpy
- Specific isobaric heat capacity
- Specific isochoric heat capacity
- Speed of sound

The standard also defines:

- Equations for calculating the relationship between saturation pressure and saturation temperature
- A restricted set of backward equations for calculating, without iteration, temperature as a function of pressure and either specific enthalpy or specific entropy.

The IAPWS has also initiated and coordinated the development of equations for transport and other properties. A set of IAPWS equations for the following properties was published, together with the IAPWS-IF97 standard, in book form in 1998. (See 'Further Reading', below):

- Dynamic viscosity
- Thermal conductivity
- Surface tension
- Static dielectric constant
- Refractive index

Water and Steam, Thermophysical Properties for MATLAB provides a suite of MATLAB functions to perform all the basic thermodynamic calculations defined by the IAPWS-IF97 standard and to calculate the transport and other properties listed above.

Units of Measurement

All functions in *Water and Steam, Thermophysical Properties for MATLAB* have been engineered for use with base units of the Système International des Unités (SI Units).

SI Units are used throughout this User's Guide.

Non-SI Units and multiples and sub-multiples of base units may be accommodated by calling the basic functions from within a user's own MATLAB functions, in which any required unit conversions may be carried out.

For pressure, the pascal (Pa) is used throughout in lieu of $N \cdot m^{-2}$.

Further Reading

With just one exception, for the calculation of thermal conductivity, all calculation functions in *Water and Steam, Thermophysical Properties for MATLAB* derive from the IAPWS-IF97 standard equations for thermodynamic properties and from the IAPWS supplementary equations for transport properties, as published in:

- Wagner W., A. Kruse, 'Properties of Water and Steam, the Industrial Standard IAPWS-IF97 for the Thermodynamic Properties and Supplementary Equations for Other Properties.' Springer-Verlag, Berlin, 1998, ISBN 3-540-64339-7

Unless stated otherwise in the text, all references in this *User's Guide* to the IAPWS-IF97 standard, or to IAPWS tables and equations refer to their representation in the above publication.

The above publication also contains detailed background information, test data, detailed descriptions of ranges of validity, detailed information about uncertainties and steam tables. Dr.-Ing. W. Wagner was head of the group that developed IAPWS-IF97.

We recommend the above publication as a companion text to *Water and Steam, Thermophysical Properties for Matlab* and to this User's Guide. It may be purchased online by following the hypertext link at the *Water and Steam, Thermophysical Properties for MATLAB* home page at the KHACE web site:

http://www.khace.com/products/watsteam/index.htm

The functions for calculating Thermal Conductivity also offer the option to calculate in accordance with:

- IAPWS Release on the Thermal Conductivity of Ordinary Water Substance (September 1998), Appendix B: 'The Recommended Interpolating Equation for Industrial Use'.

This release may be obtained from the IAPWS Secretariat. Contact details for IAPWS are at the IAPWS web site:

http://www.iapws.org

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Tutorial

Thermodynamic Properties

Regions of IAPWS-IF97

The IAPWS-IF97 standard comprises a set of equations valid in the following ranges:

$273.15\ K \le T \le 1073.15$	$p \le$	100 MPa
$1073.15\ K \le T \le 2273.15$	$p \le$	10 MPa

The entire range of validity is divided into 5 regions. The regions and their boundaries are shown in Figure 1 below.

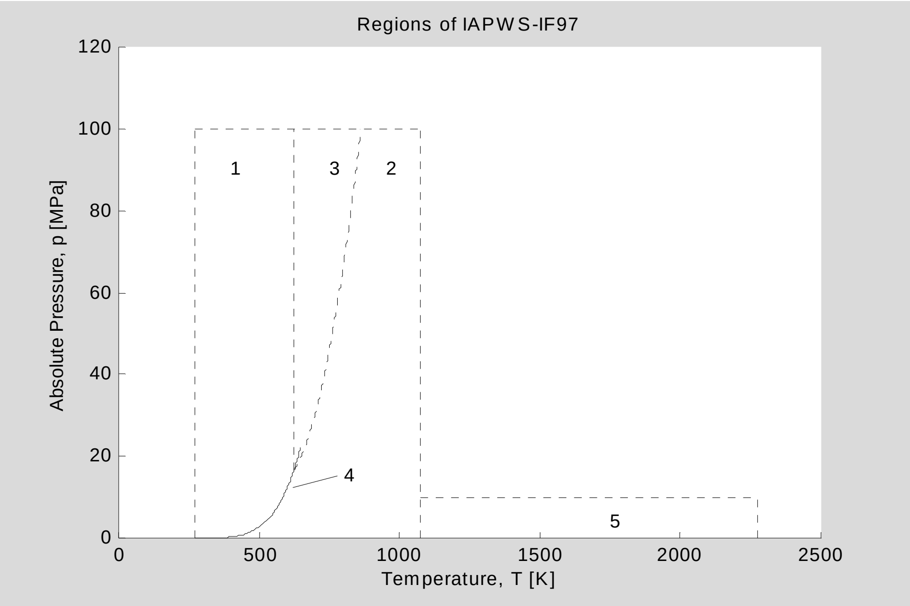


Figure 1 Regions of IAPWS-IF97

Region 1 covers the properties of compressed water, and includes the properties of the saturated liquid phase on the boundary with the saturation line (Region 4). However, Region 1 it does not cover the properties of compressed water at temperatures close to the critical temperature.

Region 2 covers the properties of superheated steam, and includes the properties of the saturated vapour phase on the boundary with the saturation line (Region 4). However, Region 2 does not cover the properties of superheated steam at temperatures near the critical temperature and pressures close to and above the critical pressure.

Region 3 is a narrow region that, for temperatures near the critical temperature and pressures close to and above the critical pressure, covers compressed water, superheated steam and part of the saturation line (Region 4)

Region 4 represents the saturation line. Within Region 4 both liquid (saturated liquid) and vapour (saturated vapour) phases may coexist, and pressure and temperature are co-dependent.

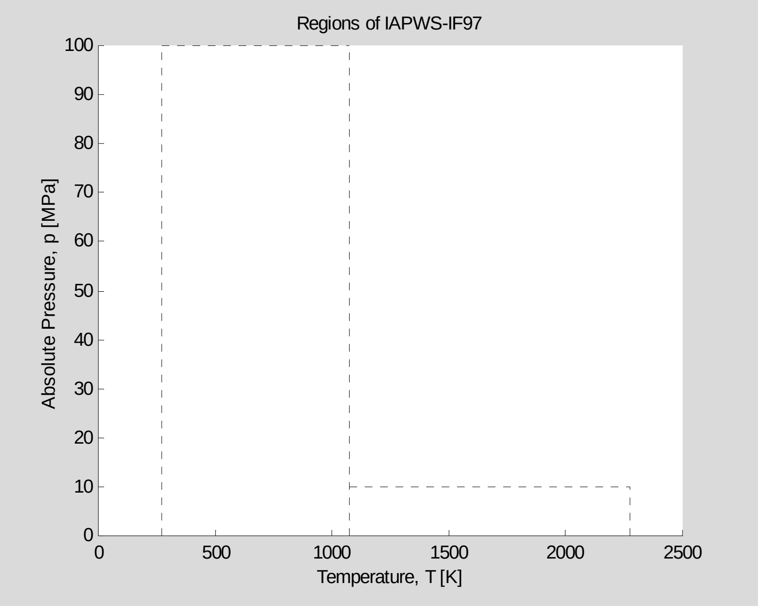
Region 5 covers the properties of superheated steam at very high temperatures.

Saturation Line and Region 2 and 3 Boundary

Figure 1 (above) may be readily created in MATLAB, using functions from *Water and Steam Thermophysical Properties for MATLAB* and simple MATLAB plotting.

The following MATLAB instructions will generate a figure, plot the boundary perimeters for the regions and label the axes:

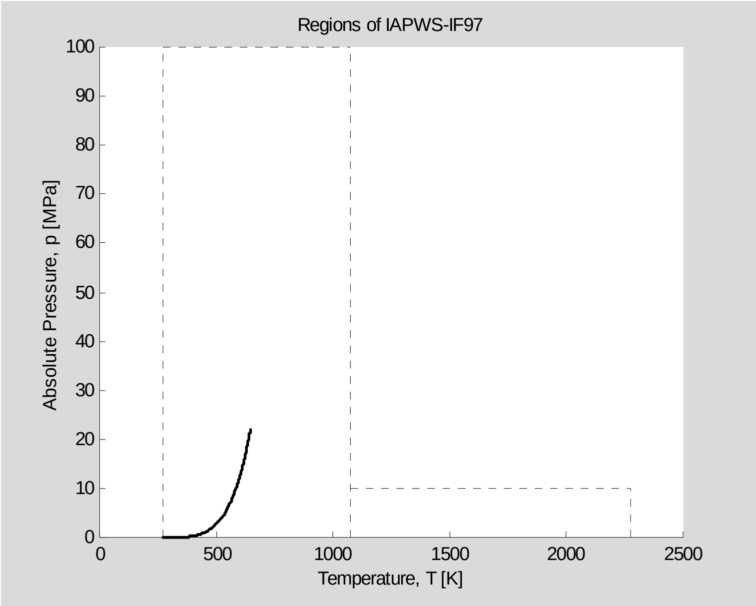
```
figure, hold on
ylabel ('Absolute Pressure, p [MPa]')
xlabel('Temperature, T [K]')
title('Regions of IAPWS-IF97')
plot([273.15,273.15],[0,100],'k:')
plot([1073.15,1073.15],[0,100],'k:')
plot([273.15,1073.15],[100,100],'k:')
plot([2273.15,2273.15],[0,10],'k:')
plot([1073.15,2273.15],[10,10],'k:')
```



The curve for Region 4 (saturation line) may be plotted using the wsr4t2p function. The wsr4t2p function calculates saturation pressure (Pa), as a function of saturation temperature (K), and will accept an array as its right-hand-side parameter. Region 4 extends from 273.15 K to 647.096 K and the pressures returned from wsr4t2p will need to be divided by 10^6 to convert Pa to MPa for the plot.

The following MATLAB instructions will plot a bold curve for Region 4:

```
hold on
ts=[273.15:647.096,647.096];
plot(ts,wsr4t2p(ts)/1e6,'k','Linewidth',2)
```

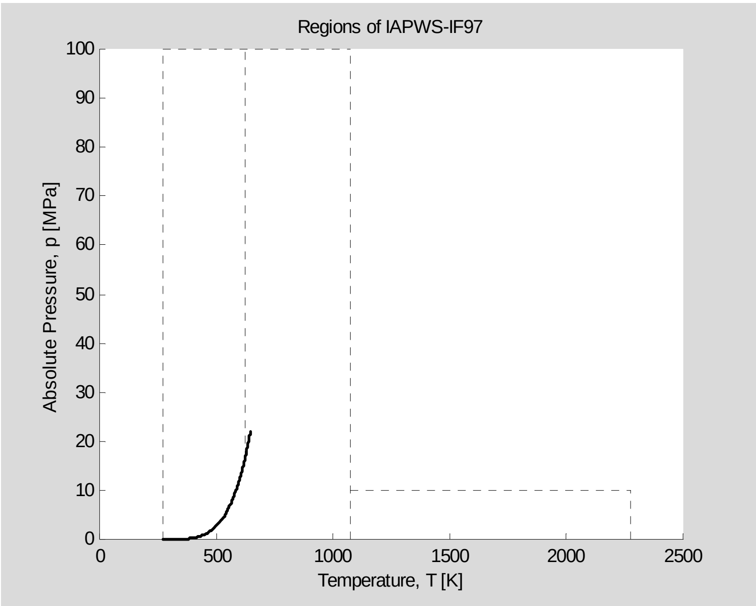


The boundary between Region 1 and Region 3 is the isotherm at 623.15 K. To plot the boundary we need to know the pressure co-ordinate on the saturation line for that temperature. The wsr4t2p function can be used again to find that pressure.

The following MATLAB instructions will display the pressure intercept with the saturation line and plot the boundary between Region 1 and Region 3:

```
tr123 = 623.15;
format long
psr123 = wsr4t2p(623.15)
plot([tr123 tr123],[psr123/1e6 100],'k:')

psr123 =
   1.652916425260448e+007
```

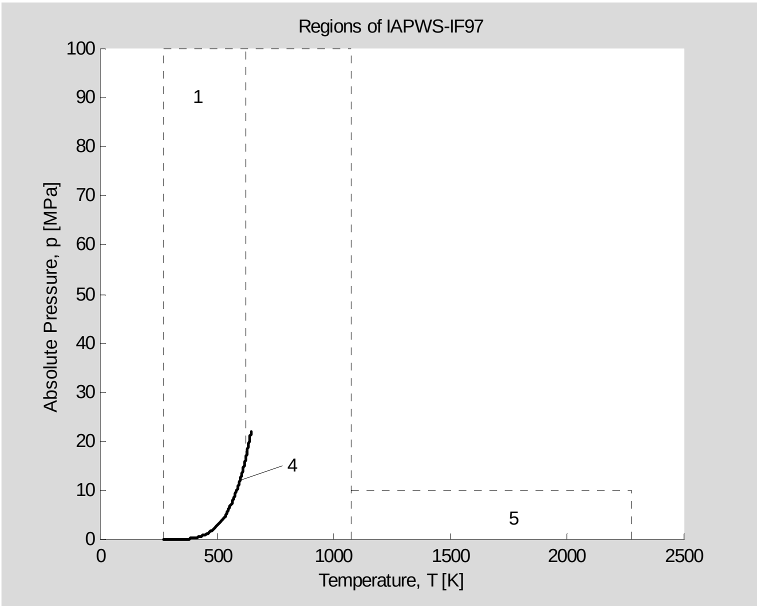


Note that the boundary between Reqion 1 and Region 3 intercepts Region 4 below the critical temperature and pressure.

We can now add some text to label those regions defined so far. To label Region 4, we can draw a line from the number '4' to a point on the saturation line at, say, 12 MPa. To do this we need the saturation temperature, which may be found using the wsr4p2t function. The wsr4p2t function calculates saturation temperature (K) as a function of saturation pressure (Pa).

The following MATLAB instructions will place text to label Region 1 and Region 5, and text and a dashed line to label Region 4:

```
text([400; 800; 1750],[90; 15; 4],['1'; '4'; '5'])
plot([780, wsr4p2t(12e6)],[15, 12],'k--')
```



To complete the map we need to plot the boundary between Regions 2 and 3, which jointly occupy and divide the area to the right and below of the saturation line.

The boundary between Region 2 (superheated steam) and Region 3 is defined by a simple quadratic pressure-temperature relationship, the B23-equation:[1]

$$\pi = n_1 + n_2\theta + n_3\theta^2$$

where $\pi = p/p^*$ and $\theta = T/T^*$ with $p^* = 1\ MPa$ and $T^* = 1\ K$ and coefficients n_1 to n_3 are defined in Table 3.9 of *Wagner and Kruse(1998)*.[2]

In *Water and Steam Thermophysical Properties for MATLAB*, the function equivalent of the B23-equation is wsb23t2p, which accepts a scalar or 2-D array of temperature (K) and returns the corresponding boundary pressure or pressures (Pa).

The intercept of the B23-equation with the saturation line is definition at temperature: 623.15 K (the same temperature as at the boundary between Region 1 and Region 3). However, the intercept with the upper pressure boundary occurs at 100 MPa, and to generate a vector of temperatures for plotting with the results from function wsb23t2p, we

[1] Wagner, W., A. Kruse, Properties of Water and Steam, The Industrial Standard IAPWS-IF97 for the Thermodynamic Properties and Supplementary Equations for Other Properties, Springer, Berlin, 1998, p.15, Auxiliary Equation: 3.6.

[2] Wagner, W., A. Kruse, Properties of Water and Steam, 1998, p.15, Table 3.9. The numerical coefficients are also accessible within *Water and Steam, Thermophysical Properties for MATLAB*. See function in the Command Reference section.

need to know the equivalent temperature. *Water and Steam Thermophysical Properties for MATLAB* also includes function wsb23p2t for calculating the inverse of the B23-equation:

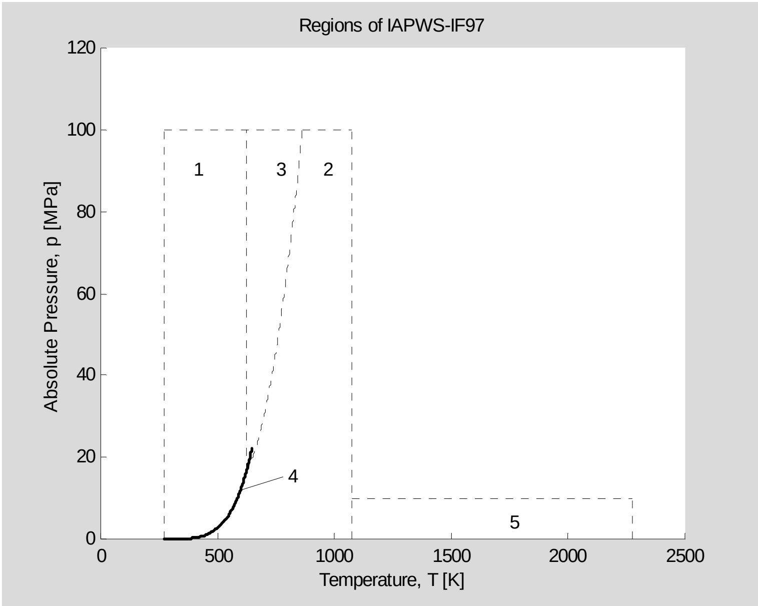
$$\theta = n_4 + [\pi - n_5)/n_3]^{0.5}$$

Function wsb23t2p accepts a scalar or vector pressure (Pa) and returns the corresponding boundary temperature or temperatures (K).

The following MATLAB instructions will find and display the intercept of the Region 2 and 3 boundary with the upper pressure limit, plot the boundary between Region 2 and Region 3, and label the regions:

```
format short
t23ul = wsb23p2t(100e6)
t23 = [623.15:t23ul, t23ul];
plot(t23, wsb23t2p(t23)/1e6,'k:')
text([750; 950],[90; 90],['3'; '2'])

t23ul =
  863.1500
```



The calculated intercept of the B23-equation with the 100 MPa upper limit confirms that the range of validity for functions wsb23t2p and wsb23p2t is 623.15 K to 863.15 K.

Determining Properties across the Regions

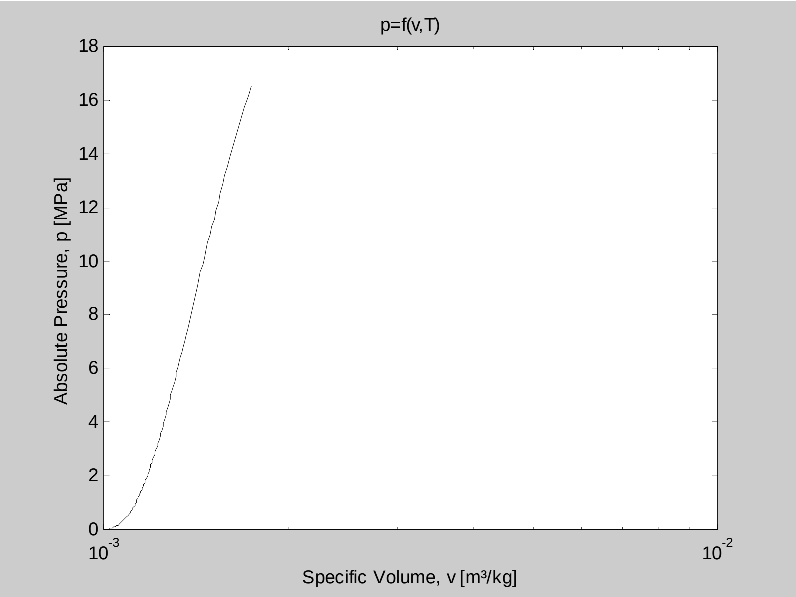
Figure 1 showed the regions of IAPWS-IF97 plotted on axes of pressure and temperature. A common way of presenting fluid properties is to plot lines of equal temperature (isotherms) on axes of pressure and specific volume. Such a plot may be readily created by employing functions from *Water and Steam Thermophysical Properties for MATLAB* to determine specific volume for a range of pressures and temperatures across the various regions.

A good place to start is by plotting the saturated liquid and saturated vapour lines. Specific volume on the saturation lines is given by the functions for the specific volume in the regions that border the lines, i.e.: Region 1, Region 2 and Region 3.

Within Region 1, the specific volume as a function of absolute pressure and temperature is given by function wsr1pt2v. Function wsr1pt2v accepts scalar inputs for pressure (Pa) and temperature (K). To use this function along the saturated liqud line, one must first generate an array of pressures and temperatures along that part of Region 4 that borders Region 1, and then apply wsr1pt2v repeatedly. The lower limit of the saturated liquid line is 273.15 K. The upper limit is at the boundary temperature of Region 1: 623.15 K.

The following MATLAB instructions will calculate pressure and temperature along the boundary between Region 1 and Region 4, then plot that part of the saturated liquid line:

```
figure
tf1=[273.15:2:623.15,623.15];
pf1=wsr4t2p(tf1);
for i=1:length(tf1),
        vf1(i)=wsr1pt2v(pf1(i),tf1(i));
end
semilogx(vf1,pf1/1e6,'k')
title('p=f(v,T)')
ylabel ('Absolute Pressure, p [MPa]')
xlabel('Specific Volume, v [m³/kg]')
```

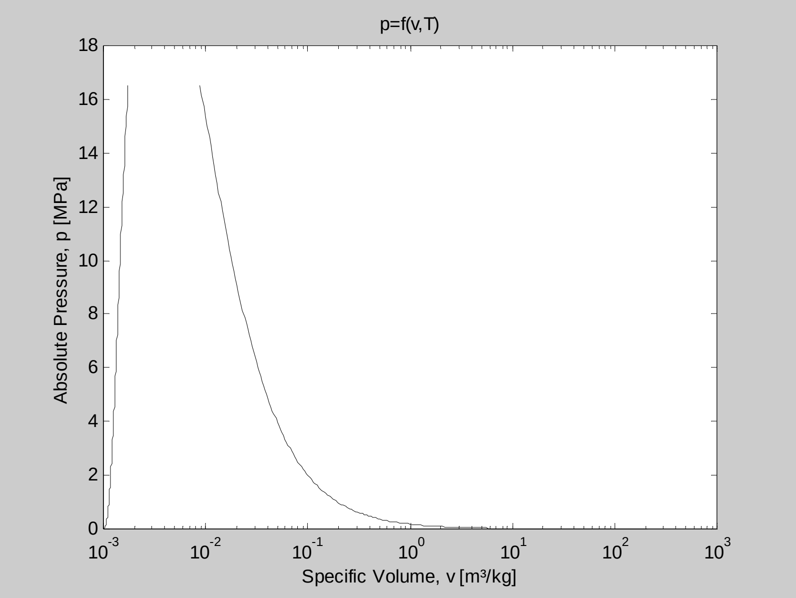


Note the use of a logarithmic scale for plotting the specific volume.

Within Region 2, the specific volume as a function of absolute pressure (Pa) and temperature (K) is given by function wsr2pt2v. To use this function along the saturated liqud line, one must again generate pressures and temperatures along that part of Region 4 that borders Region 2. The lower limit of the saturated liquid line is 273.15 K. The upper limit is at the boundary temperature of Region 3: 623.15 K.

The following MATLAB instructions will calculate pressure and temperature along the boundary between Region 2 and Region 4, then plot that part of the saturated liquid line:

```
tf2=[273.15:2:623.15,623.15];
pf2=wsr4t2p(tf2);
for i=1:length(tf2),
        vf2(i)=wsr2pt2v(pf2(i),tf2(i));
end
hold on
semilogx(vf2,pf2/1e6,'k')
```



The saturated liquid and saturated vapour lines need to be closed at the top by that part of the saturation curve that lies in Region 3. The basic equations within IAPWS-IF97 for Region 3 are different than for Region 1, 2 and 5, because they are functions of mass density (the reciprocal of specific volume) and temperature. For example: the absolute pressure within Region 3 may be calculated as a function of mass density (kg/m^{-3}) and temperature (K) using the function wsr3dt2p. This offers the possibility of plotting pressure directly as a function of specific volume.

At saturation, we know that temperature and pressure are not independent, and their relationship is defined by the Region 4 function for the saturation line: wsr4t2p. What we need to do is to reverse-solve for specific volume as a function of temperature and pressure, so that we can complete the curve. One way of doing this is to use the MATLAB function fzero, in conjunction with the function wsr3dt2p to back-calculate mass density, and thence specific volume, for pressures and temperatures on the saturation line.

On the saturation line there are two specific volumes for a given temperature and pressure: one for the saturated liquid and another for the saturated vapour. For each point in the solution, therefore, we need to specify a mass density and calculate iteratively until we find a pressure and temperature on the saturation line. *Water and Steam Thermophysical Properties for MATLAB* provides the supplementary functions wsr3vg2tg and wsr3vf2tf.

The first task is to create a logarithmically spaced vector between the end of Region 1 and the boundary of Region 2 on the saturation line. Then wsr3vg2tg must be called to solve for the saturation temperature at each specific volume.

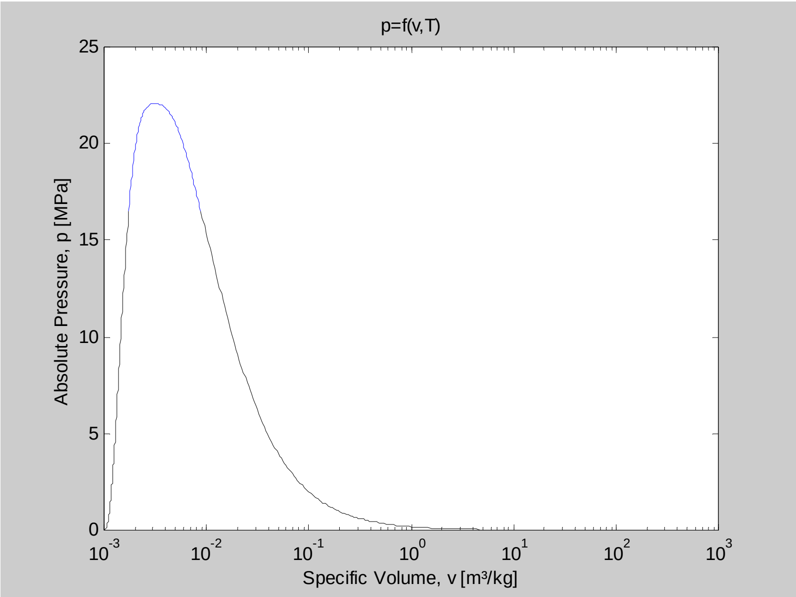
a function of absolute pressure (Pa) and temperature (K) is given by function wsr3pt2v. To use this function along the saturated liqud line, one must generate pressures and temperatures along that part of Region 3 that borders Region 4. The lower limit of the saturation line in Region 3 is 623.15 K. The upper limit is the critical temperature of steam, at 647.096 K.

The following MATLAB instructions will calculate pressure and temperature along the boundary between Region 2 and Region 4, then plot that part of the saturated liquid line:

```
% Saturated Liquid line
v3f = logspace(log10(wsr1pt2v(wsr4t2p(623.15),623.15)),log10(1/322));
for i=1:length(v3f)-1,
    t3f(i)=wsr3vf2tf(v3f(i));
end

%Saturated Vapour line
v3g = logspace(log10(1/322),log10(wsr2pt2v(wsr4t2p(623.15),623.15)));
for i=2:length(v3g),
    t3g(i)=wsr3vg2tg(v3g(i));
end

%Combine into a single curve for plotting
p3=wsr4t2p([t3f, wstcrit, t3g(2:end)]);
hold on
semilogx([v3f(1:end-1), 1/322, v3g(2:end)],p3/1e6,'b')
```



The Region 3 section of the saturation line is highlighted in blue.

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Command Reference

Summary

This section contains detailed descriptions of all functions. It begins with a list of functions grouped by subject area and continues with the reference entries in alphabetical order. Information is also available through the online help facility.

In the tables of functions for calculating thermodynamic properties from IAPWS standard IF-97:

- *'Data Functions'* refer to functions that return values for the coefficients and exponents used in equations defined in tables in [1].[3]
- *'Basic Functions'* refer to functions based on the IAPWS-IF97 'Basic Equations' for the region.
- *'Backward Functions'* refers to functions based on the IAPWS-IF97 Backward Equations for the region.
- *'Auxiliary Functions*' refers to functions based on the IAPWS-IF97 Auxiliary Equations, such as those that define the boundary between .
- *'Supplementary Functions'* refers to functions that supplement the Basic, Backward and Auxiliary Functions from IAPWS-IF97.

IAPWS-IF97 Thermodynamic Properties for Region 1 (Compressed Water)	
	Data Functions
if97t31	Coefficients and exponents from *Table 3.1*
if97t35	Coefficients and exponents from *Table 3.5*
if97t37	Coefficients and exponents from *Table 3.7*
	Basic Functions
wsr1pt2cp	Specific heat at constant pressure, $c_p = f(p,T)$
wsr1pt2cv	Specific heat at constant pressure, $c_v = f(p,T)$
wsr1pt2h	Specific enthalpy, $h = f(p,T)$
wsr1pt2k	Isentropic exponent, $\kappa = f(p,T)$
wsr1pt2s	Specific entropy, $s = f(p,T)$
wsr1pt2u	Specific internal energy, $u = f(p,T)$
wsr1pt2v	Specific volume, $v = f(p,T)$
wsr1pt2w	Speed of sound, $w = f(p,T)$

[3] These are provided primarily for verification that the correct exponents and coefficients are being used, but also for the convenience of the user who wishes to develope their own functions that require this data.

IAPWS-IF97 Thermodynamic Properties for Region 1 (Compressed Water)	
	Backward Functions
wsr1ph2t	Temperature, $T = f(p,h)$
wsr1ps2t	Temperature, $T = f(p,s)$
	Supplementary Functions
wsr1def	Definition of Region 1
wsr1pt2ddp	Isothermal compressibility $(\partial\rho/\partial p)_T = f(p,T)$
wsr1pt2dpt	Isochoric p–T gradient $(\partial p/\partial T)_\rho = f(p,T)$
wsr1tst	Test for p, T in Region 1, $flag = f(p,T)$

IAPWS-IF97 Thermodynamic Properties for Region 2 (Superheated Steam)	
	Data Functions
if97t39	Coefficients and exponents from *Table 3.9*
if97t310	Coefficients and exponents from *Table 3.10*
if97t311	Coefficients and exponents from *Table 3.11*
if97t316	Coefficients and exponents from *Table 3.16*
if97t320	Coefficients and exponents from *Table 3.20*
if97t321	Coefficients and exponents from *Table 3.21*
if97t322	Coefficients and exponents from *Table 3.22*
	Basic Functions
wsr2pt2cp	Specific heat at constant pressure, $c_p = f(p,T)$
wsr2pt2cv	Specific heat at constant pressure, $c_v = f(p,T)$
wsr2pt2h	Specific enthalpy, $h = f(p,T)$
wsr2pt2k	Isentropic exponent, $\kappa = f(p,T)$
wsr2pt2s	Specific entropy, $s = f(p,T)$
wsr2pt2u	Specific internal energy, $u = f(p,T)$

IAPWS-IF97 Thermodynamic Properties for Region 2 (Superheated Steam)	
wsr2pt2v	Specific volume, $v = f(p,T)$
wsr2pt2w	Speed of sound, $w = f(p,T)$
	Auxiliary Functions
wsb23p2t	Boundary between Regions 2 and 3, $p = f(T)$
wsb23t2p	Boundary between Regions 2 and 3, $T = f(p)$
	Supplementary Functions
wsr2def	Definition of Region 2
wsr2pt2ddp	Isothermal compressibility $(\partial\rho/\partial p)_T = f(p,T)$
wsr2pt2dpt	Isochoric p–T gradient $(\partial p/\partial T)_\rho = f(p,T)$
wsr2tst	Test for p, T in Region 2, $flag = f(p,T)$

IAPWS-IF97 Thermodynamic Properties for Region 3 (Near-Critical Steam)	
	Data Functions
if97t330	Coefficients and exponents from *Table 3.9*
	Basic Functions
wsr3dt2cp	Specific heat at constant pressure, $c_p = f(\rho,T)$
wsr3dt2cv	Specific heat at constant pressure, $c_v = f(\rho,T)$
wsr3dt2h	Specific enthalpy, $h = f(\rho,T)$
wsr3dt2k	Isentropic exponent, $\kappa = f(\rho,T)$
wsr3dt2s	Specific entropy, $s = f(\rho,T)$
wsr3dt2u	Specific internal energy, $u = f(\rho,T)$
wsr3dt2w	Speed of sound, $w = f(\rho,T)$
	Supplementary Functions
wsr3def	Definition of Region 3
wsr3tst	Test for p, T in Region 3, $flag = f(p,T)$
wsr3tf2vf	Specific volume of saturated water, $v_f = f(t_f)$

IAPWS-IF97 Thermodynamic Properties for Region 3 (Near-Critical Steam)	
wsr3pt2v	Specific volume, $v = f(p,T)$
wsr3tg2vg	Specific volume of saturated water, $v_g = f(t_g)$
wsr3vf2tf	Specific volume of saturated water, $t_f = f(v_f)$
wsr3vg2tg	Specific volume of saturated steam, $t_g = f(v_g)$

IAPWS-IF97 Thermodynamic Properties for Region 4 (Saturation Line)	
	Data Function
if97t334	Coefficients and exponents from *Table 3.34*
	Basic Function
wsr4p2t	Saturation temperature, $T_s = f(p_s)$
	Backward Function
wsr4t2p	Saturation pressure, $p_s = f(T_s)$
	Supplementary Functions
wsr4def	Definition of Region 4

IAPWS-IF97 Thermodynamic Properties for Region 5 (High-Temperature Steam)	
	Data Function
if97t338	Coefficients and exponents from *Table 3.38*
	Basic Function
wsr5pt2cp	Specific heat at constant pressure, $c_p = f(p,T)$
wsr5pt2cv	Specific heat at constant pressure, $c_v = f(p,T)$
wsr5pt2h	Specific enthalpy, $h = f(p,T)$
wsr5pt2s	Specific entropy, $s = f(p,T)$
wsr5pt2u	Specific internal energy, $u = f(p,T)$
wsr5pt2v	Specific volume, $v = f(p,T)$
wsr5pt2w	Speed of sound, $w = f(p,T)$
	Supplementary Functions
wsr5def	Definition of Region 5

IAPWS-IF97 Thermodynamic Properties for Region 5 (High-Temperature Steam)	
wsr5tst	Test for p, T in Region 1, $flag = f(p,T)$

IAPWS-IF97 Thermodynamic Properties for all regions	
wsregions	Plot a figure showing IAPWS-IF97 regions
wspt2r	Determine IAPWS-IF97 region, $r = f(p,T)$

IAPWS Transport Properties for Region 1 (Compressed Water)	
wsr1pt2lam	Thermal conductivity, $\Lambda = f(p,T)$
wsr1pt2pr	Prandtl Number Pr = $\eta \cdot c_p \cdot \lambda^{-1}$, $Pr = f(p,T)$

IAPWS Transport Properties for Region 2 (Superheated Steam)	
wsr2pt2lam	Thermal conductivity, $\Lambda = f(p,T)$
wsr2pt2pr	Prandtl Number Pr = $\eta \cdot c_p \cdot \lambda^{-1}$, $Pr = f(p,T)$

IAPWS Transport Properties for Region 3 (Near-critical Water/Steam)	
wsr3pt2lam	Thermal conductivity, $\Lambda = f(p,T)$
wsr3pt2pr	Prandtl Number Pr = $\eta \cdot c_p \cdot \lambda^{-1}$, $Pr = f(p,T)$

IAPWS Transport Properties for all regions	
wsdt2eps	Static dielectric constant, $\varepsilon = f(\rho,T)$
wsdt2eta	Dynamic viscosity, $\eta = f(\rho,T)$
wsdt2lam	Reduced thermal conductivity viscosity, $\Lambda = f(\delta,\tau,(\partial\rho/\partial p)_T,(\partial p/\partial T)_\rho)$
wsdt2psi	Reduced dynamic viscosity, $\Psi = f(\delta,\tau)$
wsldt2n	Refractive index, $n = f(\lambda,\rho,T)$,
wslpt2n	Refractive index, $n = f(\lambda,p,T)$,
wspt2lam	Thermal conductivity, $\Lambda = f(p,T)$
wspt2pr	Prandtl Number Pr = $\eta \cdot c_p \cdot \lambda^{-1}$, $Pr = f(p,T)$
wst2sig	Surface tension, $\sigma = f(T)$

References

[1] Wagner W., A. Kruse.

Thermal Conductivity

For the calculation of thermal conductivity λ, three different equations are currently in use. Two are recommended by IAPWS [2], the third is recommended by Wagner & Kruse [1].

IAPWS Equations

The two equations recommended by IAPWS are:

- The Recommended Interpolating Equation for Industrial Use.
- The Recommended Interpolating Equation for General & Scientific Use.

These Interpolating Equations are described in the IAPWS 1998 Release on Thermal Conductivity [2].

The first of these equations: the "Recommended Interpolating Equation for Industrial Use" [3], represents thermal conductivity as a function of absolute temperature and mass density; with the density computed using the IAPWS Industrial Formulation 1997 (IAPWS-IF97). **This method of of calculation of thermal conductivity is available as an option within the wspt2lam function in *Water & Steam, Thermophysical Properties for MATLAB*.** This equation yields a finite value of the thermal conductivity at the critical point, instead of the theoretically justified infinity.

The second of the IAPWS equations: the "Recommended Interpolating Equation for General & Scientific Use" [4], represents thermal conductivity as a function of absolute temperature, absolute pressure and mass density. This approach requires calculating the density, and two thermodynamic properties: isothermal compressibility $(\partial\rho/\partial p)_T$ and the partial derivative $(\partial p/\partial T)_\rho$, using the IAPWS 1995 Equations for Scientific Use (IAPWS-95) [5]. For this reason, **this method is not provided in *Water & Steam, Thermophysical Properties for MATLAB*.** However, function wsdt2lam is included for calculating the reduced thermal conductivity according to the Recommended Interpolating Equation for General & Scientific Use; because this equation is used in the equation of Wagner & Kruse (see below).

Wagner & Kruse Equations

Wagner & Kruse [1] recommend calculating thermal conductivity using the IAPWS "Recommended Interpolating Equation for General & Scientific Use" [4] (described above); but with the mass-density, and the two thermodynamic properties: isothermal compressibility $(\partial\rho/\partial p)_T$, and the partial derivative $(\partial p/\partial T)_\rho$, calculated using the IAPWS-IF97 Equations. This is explicitly allowed in the IAPWS 1998 Release [2]. **This is the default method of of calculation of thermal conductivity in *Water & Steam, Thermophysical Properties for MATLAB*.** See functions wspt2lam, wsr1pt2lam and wsr2pt2lam.

References

[1] Wagner W., A. Kruse, Section 4.2 Thermal Conductivity, p.41.
[2] IAPWS, Revised Release on the IAPS Formulation 1985 for the Thermal Conductivity of Ordinary Water Substance, London, England, September 1998.
[3] ibid. Appendix B: Recommended Interpolating Equation for Industrial Use
[4] ibid. Appendix C: Recommended Interpolating Equation for General and Scientific Use
[5] IAPWS, Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use.

Purpose Return the coefficients and exponents from Table 3.1 of IAPWS-IF97.

Syntax [i,j,n]= if97t31

Description The if97t31 function returns the coefficients n and exponents I and J from Table 3.1 of IAPWS-IF97 [1], for use in the fundamental equation for the specific Gibbs free energy, Eq.(3.1), in Region 1.

i, j and n are returned as column vectors.

Example Display the first five rows of coefficients and exponents from Table 3.1 of IAPWS-IF97:

```
format long
[i,j,n]=if97t31;
Tab=[i,j,n]';
fprintf('%4i\t%4i\t%22.14e\n',Tab(:,1:5));

   0     -2      1.46329712131670e-001
   0     -1     -8.45481871691140e-001
   0      0     -3.75636036720400e+000
   0      1      3.38551691683850e+000
   0      2     -9.57919633878720e-001
```

See Also if97t35, if97t37

References

[1] Wagner W., A. Kruse, Table 3.1, p. 11.

Purpose

Return the coefficients and exponents from Table 3.5 of IAPWS-IF97.

Syntax

```
[i,j,n]= if97t35
```

Description

The if97t35 function returns the coefficients *n* and exponents *I* and *J* from Table 3.5 of IAPWS-IF97 [1], for use in the backward equation *T(p,h)*, Eq.(3.4), for Region 1.

i, j and n are returned as column vectors.

Example

Display the first five rows of coefficients and exponents from Table 3.5 of IAPWS-IF97:

```
format long
[i,j,n]=if97t35;
Tab = [i,j,n]';
fprintf('%4i\t%4i\t%22.14e\n',Tab(:,1:5));
```

```
   0     0     -2.38724899245210e+002
   0     1      4.04211886379450e+002
   0     2      1.13497468817180e+002
   0     6     -5.84576160480390e+000
   0    22     -1.52854824131400e-004
```

See Also

if97t31, if97t37

References

[1] Wagner W., A. Kruse, Table 3.5, p.13.

Purpose Return the coefficients and exponents from Table 3.7 of IAPWS-IF97.

Syntax [i,j,n] = if97t37

Description The if97t37 function returns the coefficients *n* and exponents *I* and *J* from Table 3.7 of IAPWS-IF97 [1], for use in the backward equation *T(p,s)*, Eq. (3.5), for Region 1.

i, j and n are returned as column vectors.

Example Display the first five rows of coefficients and exponents from Table 3.7 of IAPWS-IF97:

```
format long
[i,j,n]=if97t37;
Tab = [i,j,n]';
fprintf('%4i\t%4i\t%22.14e\n',Tab(:,1:5));

   0     0     1.74782680583070e+002
   0     1     3.48069308928730e+001
   0     2     6.52925849784550e+000
   0     3     3.30399817754890e-001
   0    11    -1.92813829231960e-007
```

See Also if97t31, if97t35

References [1] Wagner W., A. Kruse, Table 3.7, p.14.