

IAPWS-IF97 Electronic Steam Tables on CD-ROM

1 Contents of the CD-ROM

The CD-ROM attached to this book contains an interactive program that enables the user to calculate all of the properties for water and steam that are contained in the book. This program is called “IAPWS-IF97 Electronic Steam Tables” and has the following features:

- The properties in the single-phase region (liquid, vapour, and supercritical region) can be calculated for any value of pressure p and temperature T . In contrast to this possibility, the tables in Part B only contain values over a fixed pressure-temperature grid.
- The properties on the saturated-liquid and saturated-vapour lines can be calculated for any value of temperature T or pressure p . Those properties for which it is reasonable can also be calculated *within* the two-phase region for given values of p or T and vapour fraction x . The tables in Part B contain only property values for the saturated liquid and saturated vapour at discrete temperatures or pressures.
- The properties cannot be calculated only for single points, but also along isolines, namely along isotherms, isobars, saturated-liquid line, and saturated vapour line. Thus, users can produce their “personal” steam tables.
- Apart from the calculation of specific properties, the program also allows to calculate molar properties. In the book only values for specific properties are given.
- Different units can be chosen for the properties to be calculated. In addition to the units used in the book that are based on SI units, several other units, including U.S. customary units, can be selected.

2 Hardware and Software Requirements

Basically, the requirements for the use of the “IAPWS-IF97 Electronic Steam Tables” are met by a PC with a standard configuration.

The following minimum configuration is required:

- Intel Pentium, AMD Duron, or AMD Athlon processor with 500 MHz
- 256 MB RAM
- Graphics card with 800 x 600 pixels
- 50 MB free hard disc space
- Operating system: Windows 98, NT 4.0 SP 6, Windows 2000, Windows XP, Windows 2003 Server

An update for the operating system Windows Vista will be made available, see item 5 “Updates.”

3 Installation

The installation of the Electronic Steam Tables should start automatically when the CD-ROM is inserted into the CD-ROM drive. If the installation program does not start after a few seconds, the user needs execute the file setup.exe on the CD-ROM to begin the installation. A guide will lead the user through the installation process.

A comprehensive help file included with the “IAPWS-IF97 Electronic Steam Tables” gives further information on the use of the program.

4 Details about the Calculations

This section gives details about the calculations of thermodynamic, transport, and other properties with the Electronic Steam Tables for the single-phase region, two-phase region, saturated-liquid line, saturated-vapour line, and the ideal-gas state. The calculations can be performed for single points and along isolines.

4.1 Calculable Properties

The following properties can be calculated:

- Saturation pressure p_s
- Saturation temperature T_s
- Specific volume v
- Density ρ
- Compression factor (real-gas factor) $z = pv/(RT)$
- Specific enthalpy h
- Specific internal energy u
- Specific entropy s
- Specific Gibbs free energy g
- Specific Helmholtz free energy f
- Specific isobaric heat capacity c_p
- Mean specific isobaric heat capacity $c_{p,m}^0$ in the ideal-gas state
- Specific isochoric heat capacity c_v
- Speed of sound w
- Isentropic exponent
- Isobaric cubic expansion coefficient $\alpha_v = v^{-1}(\partial v / \partial T)_p$
- Isothermal compressibility $\kappa_T = -v^{-1}(\partial v / \partial p)_T$
- Relative pressure coefficient $\alpha_p = p^{-1}(\partial p / \partial T)_v$
- Isothermal stress coefficient $\beta_p = -p^{-1}(\partial p / \partial v)_T$
- Joule-Thomson coefficient $\mu = (\partial T / \partial p)_h$
- Isothermal throttling coefficient $\delta_T = (\partial h / \partial p)_T$
- Fugacity f^*

- Dynamic viscosity
- Kinematic viscosity $\nu = \eta \rho^{-1}$
- Thermal conductivity
- Prandtl number $Pr = \eta c_p^{-1}$
- Thermal diffusivity $a = \lambda/(\rho c_p)$
- Dielectric constant
- Refractive index n
- Surface tension σ (only in the saturation state)

The specific properties v , h , u , s , g , f , c_p , $c_{p,m}$, c_v and the mass-based density ρ can also be calculated as molar properties.

In addition, the number of the region where the given state point is located (liquid region 1, vapour region 2, critical and supercritical region 3, two-phase region 4, or high-temperature region 5) is displayed.

4.2 Calculations in the Single-Phase Region

In the single-phase region (in the program “Range of state: Single-phase region”), properties can be calculated for given values of pressure and temperature (p, T).

The thermodynamic properties v , ρ , z , h , u , s , g , f , c_p , c_v , w , α_v , κ_T , α_p , β_p , μ , δ_T , and f^* can be calculated within the range of validity of IAPWS-IF97, i.e. within

$$\begin{array}{ll} 0 < p \leq 500 \text{ bar} & 0^\circ\text{C} \leq t \leq 2000^\circ\text{C} \\ 500 \text{ bar} < p \leq 1000 \text{ bar} & 0^\circ\text{C} \leq t \leq 800^\circ\text{C}. \end{array}$$

Values can be calculated for the dynamic viscosity η and kinematic viscosity ν in the range

$$\begin{array}{ll} 0 < p \leq 500 \text{ bar} & 0^\circ\text{C} \leq t \leq 1000^\circ\text{C} \\ 500 \text{ bar} < p \leq 1000 \text{ bar} & 0^\circ\text{C} \leq t \leq 800^\circ\text{C} \end{array}$$

and for the thermal conductivity λ , Prandtl number Pr , and thermal diffusivity a in the range

$$0 < p \leq 1000 \text{ bar} \quad 0^\circ\text{C} \leq t \leq 800^\circ\text{C}.$$

Values can be determined for the dielectric constant ϵ in the range

$$\begin{array}{ll} 0 < p \leq 500 \text{ bar} & 0^\circ\text{C} \leq t \leq 926.85^\circ\text{C} \\ 500 \text{ bar} < p \leq 1000 \text{ bar} & 0^\circ\text{C} \leq t \leq 800^\circ\text{C}, \end{array}$$

and for the refractive index n in the range

$$\begin{array}{ll} 0 < p \leq 1000 \text{ bar} & 0^\circ\text{C} \leq t \leq 500^\circ\text{C} \\ & 0.2 \mu\text{m} \leq \bar{\lambda} \leq 1.1 \mu\text{m}. \end{array}$$

The thermodynamic properties v , ρ , z , h , u , s , g , f , c_p , c_v , w , α_v , κ_T , α_p , β_p , μ , δ_T , and f^* are calculated from the IAPWS-IF97 basic equations, Eqs. (2.3), (2.6), (2.11), or (2.15), as described in Sec. 2.2. The transport properties η and λ are determined from the equations for industrial use, Eqs. (3.1) and (3.4), as described in Secs. 3.1 and 3.2. The calculation of the quantities c_p , ρ , η , and λ needed for determining the properties v , Pr , and a is described above. The properties ϵ and n are determined from Eqs. (3.9) and (3.10) as described in Secs. 3.4 and 3.5. For the calculation of n , the wavelength of light, which is marked with $\bar{\lambda}$ in the program, is

needed as a further input value. The density ρ needed in all of these equations is calculated from the IAPWS-IF97 basic equations. The calculation of the surface tension is based on Eq. (3.8) given in Sec. 3.3.

When calculating properties in the single-phase region, the saturation properties are automatically calculated as well, namely p_s , v' , and v'' for given values of t (if $0\text{ }^{\circ}\text{C} \leq t < t_c = 373.946\text{ }^{\circ}\text{C}$), and t_s for given values for p (if $0.006112127\text{ bar} \leq p < p_c = 220.64\text{ bar}$). The procedure used to determine these properties is described in the next section.

All of these properties can be calculated for single points or along isolines, namely along isobars and isotherms.

Directly at the critical point, some properties are not calculated, because IAPWS-IF97 does not yield physically meaningful values for these properties at this point.

4.3 Calculations in the Two-Phase Region

In the two-phase region (in the program “Range of state: Two-phase region”), the properties can be calculated for input values of vapour fraction x ($0 < x < 1$) and either temperature T or pressure p . The calculations can be carried out over the entire two-phase region, defined by the ranges of temperature and vapour fraction

$$0\text{ }^{\circ}\text{C} \leq t \leq 373.946\text{ }^{\circ}\text{C} \quad 0 \leq x \leq 1,$$

or by the ranges of pressure and vapour fraction

$$0.00611212677\text{ bar} \leq p \leq 220.64\text{ bar} \quad 0 \leq x \leq 1.$$

For given temperatures, the saturation pressures p_s are calculated from the IAPWS-IF97 saturation-pressure equation, Eq. (2.13).

For temperatures $t < 350\text{ }^{\circ}\text{C}$ and input values for t and p_s , all of the thermodynamic properties on the saturated-liquid and saturated-vapour lines are determined from the basic equations for regions 1 and 2, Eqs. (2.3) and (2.6), see Sec. 2.2.

For $t > 350\text{ }^{\circ}\text{C}$ and input values for t and p_s , the densities ρ' and ρ'' (and thus also the specific volumes v' and v'') are calculated by iterating the basic equation for region 3, Eq. (2.11). With the values for (ρ', t) and (ρ'', t) , the other thermodynamic properties are determined from the basic equation, Eq. (2.11).

For given pressures, the saturation temperatures t_s are calculated from the IAPWS-IF97 saturation-temperature equation, Eq. (2.14).

For pressures $p < 165.292\text{ bar}$ and input values for p and t_s , the properties on the saturated-liquid and saturated-vapour lines are determined from the basic equations for regions 1 and 2, Eqs. (2.3) and (2.6).

For $p > 165.292\text{ bar}$ and input values for p and t_s , the densities ρ' and ρ'' (and thus also the specific volumes v' and v'') are calculated by iterating the basic equation for region 3, Eq. (2.11). With the values for (ρ', t_s) and (ρ'', t_s) , the other thermodynamic properties are determined from the basic equation, Eq. (2.11).

The transport properties are determined from the equations for industrial use, Eqs. (3.1) and (3.4), as described in Secs. 3.1 and 3.2. The calculation of the quantities c_p , ρ , η , and κ needed for determining the properties v , Pr , and a is described above. The properties α and n are determined from Eqs. (3.8) and (3.10), as described in Secs. 3.4 and 3.5. The density ρ needed in all of these equations is calculated from the IAPWS-IF97 basic equations, Eqs. (2.3), (2.6), or (2.11), as described above.

The calculation of the surface tension is based on Eq. (3.9) given in Sec. 3.3.

The values of the thermodynamic properties *within* the two-phase region ($0 < x < 1$) are calculated from the relation $y = y' + x(y'' - y')$, where y stands for v , h , u , s , g , and f . The values on the saturated-liquid and saturated-vapour line are calculated as described above.

The values for the properties z , c_p , c_v , w , κ , α_v , κ_T , α_p , β_p , μ , δ_T , f^* , η , v , Pr , a , and n can only be calculated for the saturated liquid $x = 0$ (superscript ') and for saturated vapour $x = 1$ (superscript ''), because they are not defined or not reasonable *within* the two-phase region.

Directly at the critical point, some properties are not calculated, because IAPWS-IF97 does not yield physically meaningful values for these properties at this point.

4.4 Calculations Along the Saturated-Liquid and Saturated-Vapour Lines

Along the saturated-liquid line (in the program “Range of state: Saturated-liquid line”) and the saturated-vapour line (in the Electronic Steam Tables “Range of state: Saturated-vapour line”), all of the properties listed in Sec. 4.1 can be calculated for the input values of temperature or pressure. These calculations are performed in the same manner as described in Sec. 4.3 for the saturated liquid (properties marked by a single prime) and the saturated vapour (properties marked by a double prime). Here, however, the properties are not marked by any prime, because it is clear for which branch of the phase boundary the calculations are performed.

In contrast to the calculations for the two-phase region, here, calculations cannot be performed only for single points, but in the modus “Isolines” also along the entire saturated-liquid or the saturated-vapour line.

Directly at the critical point, some properties are not calculated, because IAPWS-IF97 does not yield physically meaningful values for these properties at this point.

4.5 Calculations in the Ideal-Gas State

In the ideal-gas state (in the program “Range of state: Ideal-gas state”), the thermodynamic properties v^0 , ρ^0 , h^0 , s^0 , u^0 , c_p^0 , c_v^0 , w^0 , κ^0 , and $c_{p,m}^0$ can be calculated for pressures and temperatures within the range of validity of IAPWS-IF97, see Sec. 4.2 of this Part D.

Except for the specific volume v^0 , density ρ^0 , and specific entropy s^0 , all the other ideal-gas properties are a function of temperature only. The calculation of v^0 , ρ^0 , and s^0 requires, in addition to temperature, also input values for pressure.

The properties mentioned above are calculated from Eq. (2.7) for temperatures $0^\circ\text{C} \leq t \leq 800^\circ\text{C}$, and from Eq. (2.16) for temperatures $800^\circ\text{C} < t \leq 2000^\circ\text{C}$.

The mean specific isobaric heat capacity $c_{p,m}^0$ between the reference temperature $t_0 = 0^\circ\text{C}$ and the temperature t of the given state point is defined and calculated by the relation

$$c_{p,m}^0 = c_p^0 \Big|_{t_0}^t = \frac{1}{t - t_0} \int_{T_0}^T c_p^0(T) dT.$$

The values for the specific enthalpy h^0 , the specific entropy s^0 , and the mean specific isobaric heat capacity $c_{p,m}^0$ relate to the reference temperature $t_0 = 0^\circ\text{C}$, and for s^0 , in addition, to the reference pressure $p_0 = 0.006\,112\,127$ bar. The reference values for $h^0(t_0)$ and $s^0(p_0, t_0)$ are in

accordance with the zero points of the specific internal energy and specific entropy given by Eq. (2.4).

4.6 Units

The program “IAPWS-IF97 Electronic Steam Tables” allows the use of different units for all of the properties. There are three version of default settings for the units: “Units used in the book,” “SI units,” (International System of Units) and “U.S. customary units.” The only difference between the “Units used in the book” and the “SI units” are the use of °C for temperature and bar for pressure, instead of K and MPa. Table D1 shows for the various properties the “Units used in the book” and the “U.S. customary units” and the units that can be selected instead of the default units.

Table D1 Default units and selectable units for the various properties

Property	Default units used in the book	Default U.S. customary units	Selectable units ^a
Pressure p Fugacity f^*	bar	psia	bar, mbar, N/m ² = Pa, kPa, MPa, kp/cm ² = at, atm, mm Hg = Torr, m H ₂ O, psia, in Hg, ft H ₂ O
Temperature T	°C	°F	°C, K, °F, °R
Wavelength of light λ^* ($\bar{\lambda}$ in the book)	μm	μft	μm, mm, cm, μft, in
Specific volume v	m ³ /kg	ft ³ /lb _m	m ³ /kg, cm ³ /g, ℓ/kg, ℓ/g, mℓ/g, ft ³ /lb _m , in ³ /lb _m , gal(US)/lb _m , gal(UK)/lb _m
Density ρ Isothermal stress coefficient β_p	kg/m ³	lb _m /ft ³	kg/m ³ , g/cm ³ , kg/ℓ, g/ℓ, g/mℓ, lb _m /ft ³ , lb _m /in ³ , lb _m /gal (US), lb _m /gal (UK)
Specific enthalpy h Specific internal energy u Specific Helmholtz free energy f Specific Gibbs free enthalpy g	kJ/kg	Btu/lb _m	kJ/kg, J/kg, J/g, kcal/kg, cal/kg, cal/g, Btu/lb _m , ft lb _f /lb _m
Specific entropy s Specific isobaric heat capacity c_p Specific isochoric heat capacity c_v Specific gas constant R	kJ/(kg K)	Btu/(lb _m °R)	kJ/(kg K), J/(kg K), J/(g K), kcal/(kg K), cal/(kg K), cal/(g K), Btu/(lb _m °R), ft lb _f /(lb _m °R)
Speed of sound w	m/s	ft/s	m/s, km/h, ft/s, mile/h, in/s

Continuation next page.

Table D1 – Continued

Property	Default units used in the book	Default U.S. customary units	Selectable units
Isobaric cubic expansion coefficient α_v Relative pressure coefficient α_p	1/K	1/°R	1/K, 1/°R
Isothermal compressibility κ_T	1/kPa	1/psia	1/kPa, 1/MPa, 1/bar, 1/psia
Joule-Thomson coefficient μ	K/kPa	°R/psia	K/kPa, K/MPa, K/bar, °R/psia
Isothermal throttling coefficient δ_T	kJ/(kg kPa)	Btu/(lb _m psia)	kJ/(kg kPa), kJ/(kg MPa), kJ/(kg bar), kcal/(kg bar), Btu/(lb _m psia)
Dynamic viscosity η	Pa s	lb _m /(ft s)	Pa s, mPa s, μPa s, g/(cm s) = poise, kg/(m s), poise (P), cP, mP, N s/m ² , mN s/m ² , μN s/m ² , lb _m /(ft s), lb _m /(ft h)
Kinematic viscosity ν	m ² /s	ft ² /s	m ² /s, cm ² /s = stoke, mm ² /s, m ² /h, stoke (St), cSt, ft ² /s, ft ² /h
Thermal conductivity λ	W/(m K)	Btu/(ft h °R)	W/(m K), kcal/(m h K), cal/(cm s K), Btu/(ft h °R)
Thermal diffusivity α	m ² /s	ft ² /s	m ² /s, cm ² /s, mm ² /s, m ² /h, ft ² /s, ft ² /h
Surface tension σ	N/m	lb _f /ft	N/m, mN/m, lb _f /ft
Molar mass M	kg/kmol	lb _m /lbmol	kg/kmol, kg/mol, g/mol, lb _m /lbmol
Compression factor z Isentropic exponent κ Prandtl number Pr Dielectric constant ε Refractive index n	—	—	—

^a lb_m = pound (mass), lb_f = pound (force), ℓ = liter.

The unit of a property can be chosen by clicking on the unit displayed for the respective property. A menu bar showing the units that can be selected will be opened and the desired unit can be clicked.

5 Updates

Updates will be released as soon as they become necessary. It is advisable to check from time to time whether an update is available. Please follow the steps below to update your software.

The user should first check whether an update is available or not. To do this, please click in the menu bar of the main form of the Electronic Steam Tables on “?” and after that on “Update check.” The program will check for an update if the computer is connected to the internet. If an update is available, a corresponding message will appear in the window. To download this update, click on the link located in the upper right corner of the window, which will lead you to the download website of the International Steam Tables: <http://www.international-steam-tables.com>. On this website click “Update” and download the update. The downloaded file has to be executed to install the update automatically. The program should be closed before starting the installation process.

6 Extended Software Packages for IAPWS-IF97 and IAPWS-95

The authors’ groups have developed extended software for calculating values for the thermodynamic properties of water and steam based on the industrial formulation IAPWS-IF97 and on the scientific formulation IAPWS-95 [8, 9]. These software packages can calculate not only the thermodynamic and transport properties for the input variables (p, T) , but also for (p, h) , (p, s) , (h, s) , etc.

The software packages comprise the following sorts of software:

- Interactive programs that can also generate thermodynamic diagrams.
- Libraries that can be integrated into user specific programs written, for example, in Fortran, Pascal (Delphi), C++, or Visual Basic under the operating systems Windows®, Unix®, Linux®, and Mac OS®. The libraries contain functions to calculate more than 20 thermodynamic and transport properties, but also thermodynamic derivatives, and backward functions. These functions can be used for calculating heat cycles, boilers, steam turbines, etc.
- Dynamic-Link Libraries (DLLs) that can be integrated into user specific programs under the operating system Windows®.
- Add-Ins to add the functions of the DLL to Excel®.
- Add-Ins to combine the DLL with Mathcad® and Matlab®.
- Programs that can be used as electronic steam tables for some types of pocket calculators from Texas Instruments, Hewlett-Packard, and Casio.

Further information on these software packages is given at the website:

<http://www.international-steam-tables.com>.