Hans-Joachim Kretzschmar · Wolfgang Wagner

International Steam Tables

Properties of Water and Steam based on the Industrial Formulation IAPWS-IF97

3rd Edition

Tables, Algorithms, and Diagrams

All of the equations of IAPWS-IF97 including a complete set of supplementary backward equations for fast calculations of heat cycles, boilers, and steam turbines

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Preface to the Third Edition

The international research regarding the thermophysical properties of water and steam has been coordinated by the International Association for the Properties of Water and Steam (IAPWS). IAPWS is responsible for the international standards for thermophysical properties. These standards and recommendations are given in the form of releases, guidelines, and advisory notes. In 1997, IAPWS adopted the Release "IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam" called IAPWS-IF97 for short.

The first edition of this book, published in 1998, described IAPWS-IF97 as it was adopted by IAPWS in 1997. In 2008, the second edition was published. Apart from incorporating all the "supplementary" backward equations developed after the adoption of IAPWS-IF97, it was a significant extension of the first edition; for details see the preface to the second edition.

In the third edition, apart from some printing errors, the following changes have been made. In *Part A*, all revisions of the Releases and Supplementary Releases adopted after 2008 were taken into account. In connection with the basic equations, equations for calculating the relative pressure coefficient and the isothermal stress coefficient and thus the corresponding partial derivatives have been included. The most important change is the incorporation of the current equation of the thermal conductivity of water and steam adopted by IAPWS in 2011. In *Part B*, the tables of the thermal conductivity and the Prandtl number that contains the thermal conductivity have been recalculated. Further changes are the (partly significant) reduction of the sizes of the tables combined with adding seven new tables of properties that were not yet considered in the second edition. In *Part C*, the diagram for the thermal conductivity is recalculated due to the new equation for this property. Because of the thermal conductivity, the diagrams for the quantities Prandtl number and thermal diffusivity, had also to be recalculated.

The Parts D (IAPWS-IF97 Electronic Steam Tables on CD-ROM) and E (Wall Charts of the Properties of Water and Steam) of the second edition were omitted. However, information how to calculate property values for water and steam online and how to obtain copies of coloured wall charts of the Mollier *h-s* diagram, the *T-s* diagram, and the $\log(p)$-*h* diagram are given at http://www.international-steam-tables.com. In addition, there is also information on property-calculation software for Windows and Linux applications and for IOS and Android smart phones, tablets, and pocket calculators.

We are grateful to the members of the IAPWS Working Groups "Thermophysical Properties of Water and Steam" and "Industrial Requirements and Solutions" for fruitful discussions. Our warmest thanks are dedicated to Dr. M. Kunick and Dr. S. Herrmann for formatting the text of Part A and the tables as Microsoft Excel sheets for Part B, and for their help in revising the pressure-temperature diagrams in Part C of the book. We thank Mr. M. Sünder for reprogramming all of the equations and tables in Parts A and B of the book. We would also like to thank Mrs. R. Gölzenleuchter very much for producing all of the figures.

Zittau and Bochum, December 2018

H.-J. Kretzschmar
W. Wagner

Preface to the Second Edition

The international research regarding the thermophysical properties of water and steam has been coordinated by the International Association for the Properties of Water and Steam (IAPWS). IAPWS is responsible for the international standards for thermophysical properties. These standards and recommendations are given in the form of releases, guidelines, and advisory notes. One of the most important standards in this sense is the formulation for the thermodynamic properties of water and steam for industrial use.

In 1997, IAPWS adopted the "IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam" for industrial use, called IAPWS-IF97 for short. The formulation IAPWS-IF97 replaced the previous industrial formulation IFC-67 published in 1967.

After the adoption of IAPWS-IF97 in 1997, further so-called backward equations were developed. These studies were coordinated by the IAPWS Task Group on Supplementary Backward Equations for IAPWS-IF97 chaired by one of the authors of this book (H.-J. K.). The final form of these equations is based on contributions by

J. R. Cooper	K. Knobloch	I. Stöcker
A. Dittmann	H.-J. Kretzschmar	R. Span
D. G. Friend	R. Mareš	W. Wagner
J. S. Gallagher	K. Miyagawa	I. Weber
A. H. Harvey	N. Okita	

In addition to these scientists, many other IAPWS colleagues, particularly the members of the working group "Industrial Calculations" (chairman up to 2001: B. Rukes, chairman from 2001 to 2003: K. Miyagawa, and chairman from 2004 onwards: Bill Parry) from 2002 onwards renamed in "Industrial Requirements and Solutions", and the working group "Thermophysical Properties of Water and Steam" (chairman up to 2000: J. R. Cooper, chairman from 2000 to 2005: D. G. Friend, and chairman from 2005 onwards: H.-J. Kretzschmar), have contributed to the entire success of this IAPWS project; we appreciate their contribution very much. We are particularly grateful to the chairman of the evaluation task group, K. Miyagawa, for his exceptional efforts in testing these backward equations to ensure that they fulfill all requirements and checking the drafts of the several supplementary releases.

In 1998, Springer-Verlag published the book "Properties of Water and Steam" authored by W. Wagner and A. Kruse. This book described the industrial formulation IAPWS-IF97 as it was adopted by IAPWS in 1997. This new book is considered to be the second edition of the book published in 1998, although it has a different title and authorship and is only in English and no longer bilingual English/German. This second edition describes the industrial formulation in its current form, thus including all of the new so-called backward equations adopted by IAPWS between 2001 and 2005.

In addition to IAPWS-IF97, the industrial standard for the *thermodynamic* properties of water and steam, the most recent equations for the *transport* properties dynamic viscosity and thermal conductivity are also presented. Moreover, equations for the surface tension, dielectric constant,

and refractive index are given.

In contrast to the first edition, this second edition contains a number of extensions and new parts, namely:

- Incorporation of all "supplementary" backward equations.
- Inclusion of the uncertainty of the specific enthalpy into the uncertainty values of IAPWS-IF97 for the most important properties.
- Formulas to calculate all partial derivates of the eight most important thermodynamic properties.
- Additional properties in the steam tables.
- Incorporation of the new basic equation for the high-temperature region (1073.15 K to 2273.15 K) with pressures up to 50 MPa (previously up to 10 MPa).
- Pressure-temperature diagrams with isolines of all properties contained in the steam tables and further properties.
- A compact disc (CD) providing the interactive program "IAPWS-IF97 Electronic Steam Tables" for the calculation of all properties (contained in the book) dependent on freely selectable pressures and temperatures in the single-phase region and on pressure or temperature along the saturated-vapour and saturated-liquid lines. Those properties for which it is reasonable can also be calculated within the two-phase region for given values of pressure or temperature and vapour fraction.

We are very grateful to Dr. K. Knobloch who developed the supplementary backward equations in her dissertation. We would like to thank Mr. M. Kunick for calculating and formatting the tables as Microsoft Excel sheets for Part B. We are very grateful to Dr. I. Stöcker, Dr. K. Knobloch, Ms. M. Weidner, and Mr. S. Buchholz for their help in producing all of the pressure-temperature diagrams in Part C of the book. Our warmest thanks are dedicated to Dr. U. Overhoff for his assistance in preparing the "IAPWS-IF97 Electronic Steam Tables" on the CD in Part D and for several checkups, and to Dr. I. Stöcker for her help in producing the large size Mollier *h-s* and *T-s* diagrams, which are included as attachments to the book. We thank Mr. R. Preusche, Mr. M. Markward, and Mr. B. Salomo for reprogramming all of the equations presented in the book. We would also like to thank Mrs. B. Esch for typing the text of the manuscript and Mrs. R. Gölzenleuchter for producing all of the figures. Our thanks go to Dr. O. Kunz for his help in creating the electronic printing version of Part A of the manuscript. Finally, we are grateful to Dr. E. W. Lemmon and Mrs. R. Smith for carefully reading the manuscript and for a number of suggestions on improving the English style.

One of us (H.-J. Kretzschmar) is particularly grateful to the Saxon State Ministry for Science and Art for the financial support of the development of the supplementary backward equations at the Zittau/Görlitz University of Applied Sciences from 2001 to 2003.

Bochum and Zittau, November 2007

W. Wagner
H.-J. Kretzschmar

Preface to the First Edition

In 1997, the International Association for the Properties of Water and Steam (IAPWS) adopted a new formulation for the thermodynamic properties of water and steam for industrial use. This formulation is called "IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam" and "IAPWS Industrial Formulation 1997" or "IAPWS-IF97" for short. The new formulation IAPWS-IF97 replaces the previous industrial formulation, IFC-67, that has formed the basis for power-plant calculations and other industrial applications since the late 1960's. IAPWS-IF97 improves significantly both the accuracy and the speed of the calculation of thermodynamic properties. The differences from IFC-67 will require many users, particularly boiler and turbine manufacturers but also power-station companies and corresponding engineering offices, to modify design and application codes. In addition to these applications, IAPWS-IF97 is also of importance for energy-engineering applications in chemical industry and in other branches of industry. Therefore, this book presents the individual equations of IAPWS-IF97 for calculating the thermodynamic properties of water and steam for industrial use.

The IAPWS Industrial Formulation 1997 was developed in an international research project. This development was coordinated by the IAPWS Task Group "New Industrial Formulation" chaired by one of the authors of this book (W. W.). The final form of IAPWS-IF97 is based on contributions and equations by

J. R. Cooper	R. Mareš	Y. Takaishi
A. Dittmann	K. Oguchi	I. Tanishita
J. Kijima	H. Sato	J. Trübenbach
H.-J. Kretzschmar	I. Stöcker	W. Wagner
A. Kruse	O. Šifner	Th. Willkommen.

Besides these "developers" many other IAPWS colleagues, particularly the members of the two working groups "Industrial Calculations" and "Thermophysical Properties of Water and Steam", contributed to the entire success of this comprehensive project; we appreciate their contribution very much. We are especially grateful to the chairmen of these two working groups, B. Rukes and J. R. Cooper. In addition, we would like to thank the members of the IAPWS Task Group "New Industrial Formulation - Evaluation" for testing IAPWS-IF97 regarding the fulfilment of requirements and checking the influence on real power-cycle calculations; concerning these important pieces of work we are particularly grateful to the chairman of this task group, K. Miyagawa, and his colleagues R. Spencer, R. B. McClintock, and H. W. Bradly for their exceptional efforts.

In addition to IAPWS-IF97, the industrial standard for the thermodynamic properties of water and steam, the most recent equations for the transport properties dynamic viscosity and thermal conductivity are also presented. Moreover, equations for the surface tension, static dielectric constant, and refractive index are given.

The text of this book is bilingual. Part A contains the description of the above mentioned equations for the thermophysical properties in English and Part B the corresponding description

in German. Comprehensive tables of the most important thermophysical properties of water and steam are given in Part C in both languages.

The values in the tables of Part C were exclusively calculated from the corresponding equations summarized in Part A and Part B, respectively. These tables, which are mainly based on the new industrial formulation IAPWS-IF97, replace the tables "Properties of Water and Steam in SI-Units" prepared by E. Schmidt and edited by U. Grigull (Springer-Verlag Berlin Heidelberg New York, R. Oldenbourg München, Fourth, Enlarged Printing, 1989) which are based on the previous industrial formulation IFC-67.

We wish to express our warmest thanks to Mr. C. Bonsen for his help in handling the computer programs for calculating the transport properties and for producing all the tables. We would also like to thank Mrs. A.-M. Sieg for typing the text of the manuscript. We are particularly grateful to the Deutsche Forschungsgemeinschaft for their financial support of that part of the development of IAPWS-IF97 which was carried out at the Ruhr-University Bochum.

Bochum, February 1998

W. Wagner
A. Kruse

Contents

Nomenclature

Quantities

A	Function
a	Thermal diffusivity, $a = \lambda/(\rho\, c_p)$
a	Coefficient
B	Function
c_p	Specific isobaric heat capacity
$c^{\circ}_{p,\mathrm{m}}$	Mean specific isobaric heat capacity in the ideal-gas state
c_v	Specific isochoric heat capacity
CTR	Computing-Time Ratio
f	Specific Helmholtz free energy, $f = u - Ts$
f^*	Fugacity
g	Specific Gibbs free energy, $g = h - Ts$
$\overline{g}$	$\overline{g}$-factor of Harris and Alder
h	Specific enthalpy
Δh_v	Specific enthalpy of vaporization, $\Delta h_\mathrm{v} = h'' - h'$
I	Exponent
i	Serial number; Exponent
J	Exponent
j	Serial number; Exponent
k	Boltzmann's constant
M	Molar mass
N_A	Avogadro's number
n	Refractive index
n	Coefficient
Pr	Prandtl number, $Pr = \eta\, c_p\, \lambda^{-1}$
p	Pressure
R	Specific gas constant
R_m	Molar gas constant
s	Specific entropy
Δs_v	Specific entropy of vaporization, $\Delta s_\mathrm{v} = s'' - s'$
T	Thermodynamic temperature[1]
t	Celsius temperature, $t/°\mathrm{C} = T/\mathrm{K} - 273.15$
u	Specific internal energy
v	Specific volume
w	Speed of sound

[1] All temperature values given in this book are temperatures according to the International Temperature Scale of 1990 (ITS-90)

x Vapour fraction
x Arbitrary state variable
y Arbitrary state variable
z Compression factor, $z = pv/(RT)$
z Arbitrary state variable
α Mean molecular polarizability of the isolated water molecule
α_p Relative pressure coefficient, $\alpha_p = p^{-1}(\partial p/\partial T)_v$
α_v Isobaric cubic expansion coefficient, $\alpha_v = v^{-1}(\partial v/\partial T)_p$
β Transformed pressure, Eq. (2.12a)
β_p Isothermal stress coefficient, $\beta_p = -p^{-1}(\partial p/\partial v)_T$
γ Dimensionless Gibbs free energy, $\gamma = g/(RT)$
Δ Difference in any quantity
δ Reduced density, $\delta = \rho/\rho^*$
δ_T Isothermal throttling coefficient, $\delta_T = (\partial h/\partial p)_T$
ε Dielectric constant
(relative static dielectric constant or relative static permittivity)
ε_0 Permittivity of vacuum (electric constant)
η Dynamic viscosity
η Reduced enthalpy, $\eta = h/h^*$
θ Reduced temperature, $\theta = T/T^*$
ϑ Transformed temperature, Eq. (2.12b)
κ Isentropic exponent, $\kappa = -vp^{-1}(\partial p/\partial v)_s$
κ_T Isothermal compressibility, $\kappa_T = -v^{-1}(\partial v/\partial p)_T$
λ Thermal conductivity
Λ Reduced thermal conductivity, $\Lambda = \lambda/\lambda^*$
$\bar{\lambda}$ Wavelength of light
$\bar{\Lambda}$ Reduced wavelength of light, $\bar{\Lambda} = \bar{\lambda}/\bar{\lambda}^*$
μ Joule-Thomson coefficient, $\mu = (\partial T/\partial p)_h$
μ Dipole moment of the isolated water molecule
ν Kinematic viscosity, $\nu = \eta\rho^{-1}$
π Reduced pressure, $\pi = p/p^*$
ρ Mass density
σ Surface tension
σ Reduced entropy, $\sigma = s/s^*$
τ Inverse reduced temperature, $\tau = T^*/T$
ϕ Dimensionless Helmholtz free energy, $\phi = f/(RT)$
Ψ Reduced dynamic viscosity, $\Psi = \eta/\eta^*$
ω Reduced volume, $\omega = v/v^*$

Superscripts

o Ideal-gas part; ideal gas
r Residual part
max Maximum value of a quantity
min Minimum value of a quantity

*	Reducing quantity
′	Saturated-liquid state
″	Saturated-vapour state

Subscripts

ad	Adiabat
b	Normal boiling point
c	Critical point
h	At constant specific enthalpy
ind	Industrial equation for λ
m	State on the melting line
m	Mean value
max	Maximum value of a quantity
p	At constant pressure
perm	Permissible
RMS	Root-mean-square value of a quantity, see below
ρ	At constant density
s	Saturation state
s	At constant specific entropy
sub	State on the sublimation line
t	Triple point
T	At constant temperature
v	At constant specific volume

Root-mean-square value:

$$(\Delta x)_{\mathrm{RMS}} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(\Delta x_n)^2}\ ,$$

where Δx_n can be either absolute or percentage differences of the corresponding property x; N is the number of Δx_n values (depending on the property, between 10 million and 100 million points are uniformly distributed over the respective range of validity)