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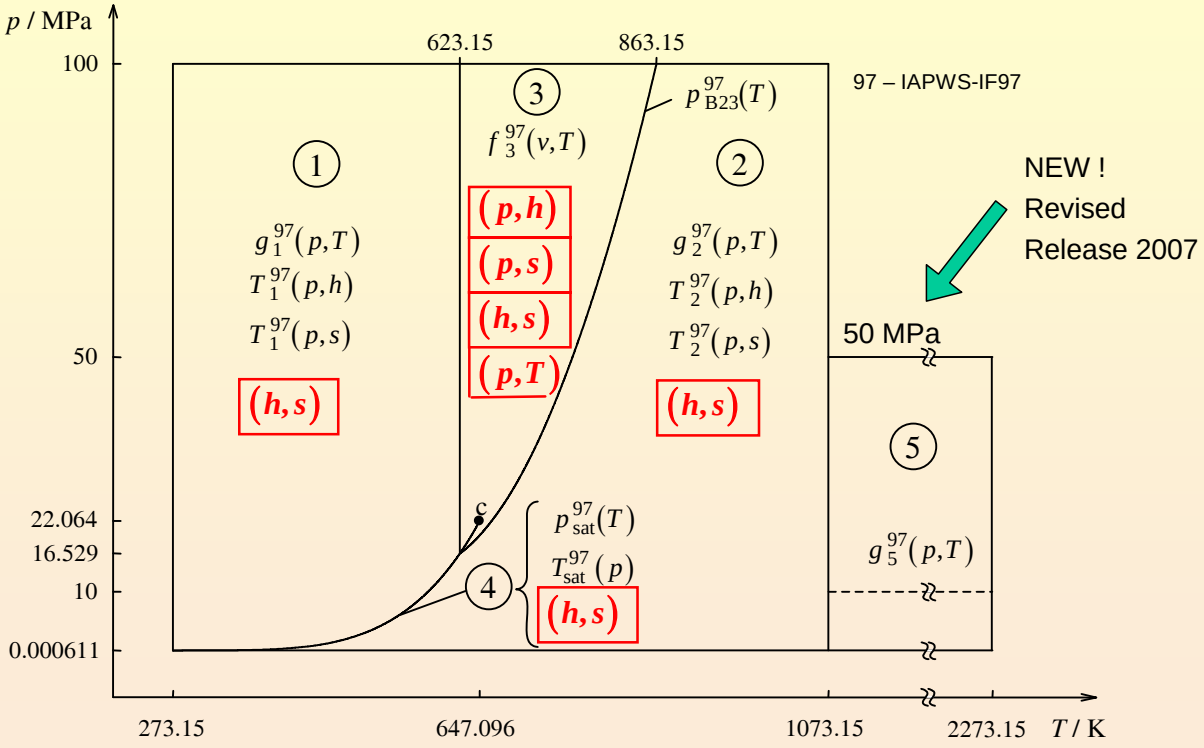
Supplementary Backward Equations for the Industrial Formulation IAPWS-IF97 of Water and Steam for Fast Calculations of Heat Cycles, Boilers, and Steam Turbines

Contents

IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam IAPWS-IF97

Result of international surveys in industry, organized by IAPWS



Requirements for Backward Equations

1. Extremely high numerical consistency

→ Deviation between the backward equation and the related fundamental equation

Example: Backward equations $T(p,h)$

$|\Delta T| = |T - T(p,h)| < 25$ mK (< 10 mK for steam turbine calculations)

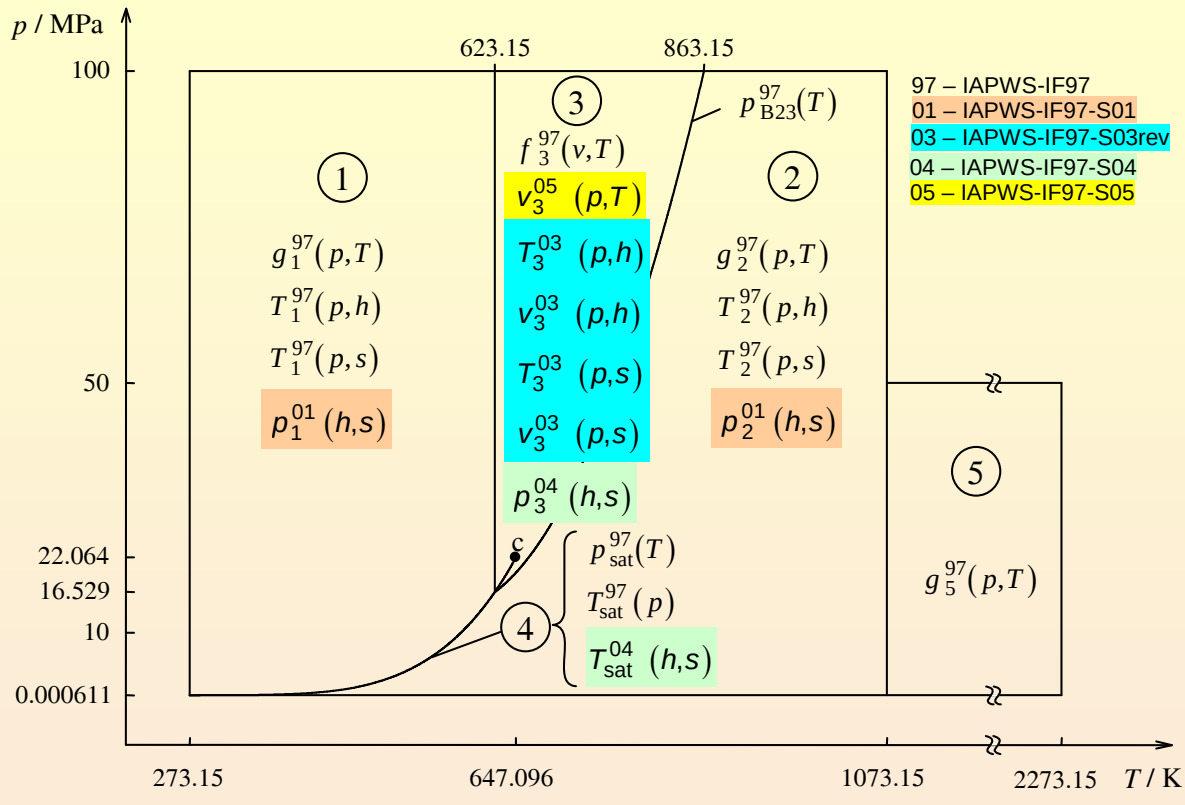
where $h = h(p,T)$ derived from the fundamental equation $g(p,T)$

→ Determined by IAPWS based on an international survey in industry

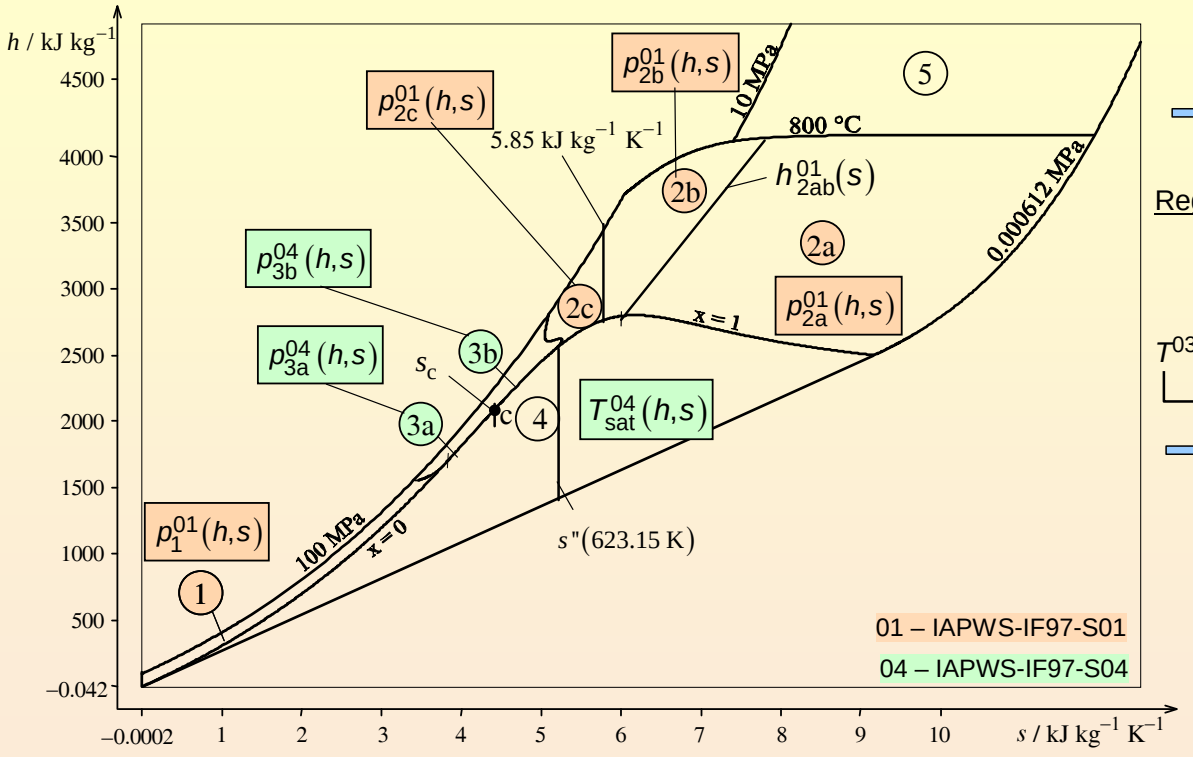
Challenge: The numerical consistency is more than one magnitude higher than the accuracy of the properties themselves

2. Calculation of the backward equations should be much faster than the corresponding iterations of the fundamental equations

Supplementary Backward Equations for IAPWS-IF97



Backward Equations for Functions of Enthalpy and Entropy (*h*,*s*)



Regions 1, 2

$p^{01}(h,s)$

$T^{97}(p,h)$

$g^{97}(T,p)$

Region 3

$p^{04}(h,s)$,

$T^{03}(p,h)$, $v^{03}(p,s)$

$f^{97}(T,v)$

Region 4

$T^{04}_{sat}(h,s)$

$p^{97}_{sat}(T_{sat})$

$$x = \frac{h - h'}{h'' - h'}$$

Backward Equations $p(h,s)$ and $T_{sat}(h,s)$

Structures

$$\frac{p(h,s)}{p^*} = \left[\sum_{i=1}^{N} n_i \left(\frac{h}{h^*} + a\right)^{I_i} \left(\frac{s}{s^*} + b\right)^{J_i}\right]^c$$

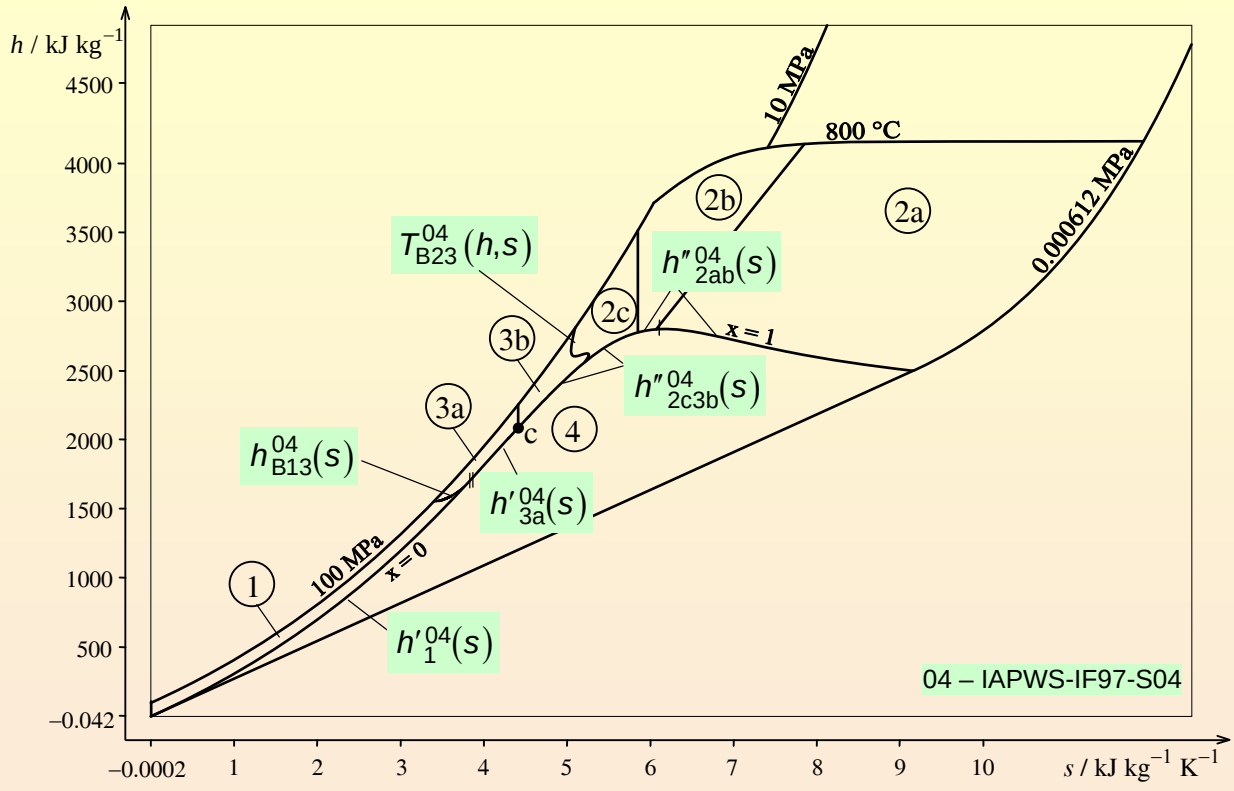
$$\frac{T_{sat}(h,s)}{T^*} = \sum_{i=1}^{36} n_i \left(\frac{h}{h^*} + a\right)^{I_i} \left(\frac{s}{s^*} + b\right)^{J_i}$$

Numerical consistency

Equation	N	a	b	c	$\lvert\Delta p/p\rvert_{max}$ %	$\lvert\Delta p/p\rvert_{tol}$ %
$p^{01}_1(h,s)$ $p \le 2.5$MPa	19	0.05	0.05	1	0.55	0.60
$p > 2.5$MPa					14 kPa	15 kPa
$p^{01}_{2a}(h,s)$	29	– 0.5	– 1.2	4	0.0029	0.0035
$p^{01}_{2b}(h,s)$	33	– 0.6	– 1.01	4	0.0034	0.0035
$p^{01}_{2c}(h,s)$	31	– 0.7	– 1.1	4	0.0063	0.0088
$p^{04}_{3a}(h,s)$	33	– 1.01	– 0.75	1	0.0070	0.01
$p^{04}_{3b}(h,s)$	35	– 0.681	– 0.792	– 1	0.0084	0.01

Equation					$\lvert\Delta T\rvert_{max}$ mK	$\lvert\Delta T\rvert_{tol}$ mK
$T^{04}_{sat}(h,s)$ $s \le 5.85$ kJ kg^{-1}K^{-1}	36	– 0.119	– 1.07		0.86	25
$s > 5.85$ kJ kg^{-1}K^{-1}					0.67	10

Region Boundary Equations for Functions of Enthalpy and Entropy (*h*,*s*)



Computing Time in Comparison with Iteration IAPWS-IF97 Fundamental Equations

Computing Time Ratio (*CTR*)

$$CTR = \frac{Compting\ time\ of\ fundamental\ eq.}{Computing\ time\ of\ backward\ eq.}$$

Region	*CTR* Backward Function (*p*,*h*)	(*p*,*s*)	(*h*,*s*)	(*p*,*T*)
① Liquid	25	38	35	-
② Vapor	11	14	46	-
③ Critical and supercritical	14	14	10	17
④ Two-phase	-	-	14	-

Calculations of heat cycles, boilers and steam turbines may be 2 to 3 times faster when using the backward and boundary equations

Summary

- Backward and region-boundary equations for the functions of (p,h), (p,s), (h,s) and (p,T) have been developed.
- The equations were adopted by IAPWS as four supplementary releases to the Industrial Formulation IAPWS-IF97,
  available at: www.iapws.org
- Their numerical consistency is sufficient for most applications in heat-cycle, boiler, and steam-turbine calculations.
- Using the equations, the properties as functions of (p,T), (p,h), (p,s), and (h,s), including determination of the region, can be calculated without iterations.
- Resulting, process calculations are between 2 and 3 times faster when using the supplementary backward and boundary equations.
- The equations were published in the ASME Journal of Engineering for Gas Turbines and Power in the issues of July 2006, January 2007, and October 2007.
- The book "International Steam Tables" contains a comprehensive description of IAPWS-97 and all backward and region-boundary equations.
  For more details see: www.international-steam-tables.com

Paper available at: www.thermodynamics-zittau.de.