SUPPLEMENTARY BACKWARD EQUATIONS FOR THE INDUSTRIAL FORMULATION IAPWS-IF97 OF WATER AND STEAM FOR FAST CALCULATIONS OF HEAT CYCLES, BOILERS, AND STEAM TURBINES

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In 1997, the International Association for the Properties of Water and Steam (IAPWS) adopted the "IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam" (IAPWS-IF97). The IAPWS-IF97 contains fundamental equations $g(p,T)$ for liquid region 1, vapor region 2 and high-temperature region 5, a fundamental equation $f(v,T)$ for the critical and supercritical regions (region 3) and an equation pair for saturation pressure $p_{\text{sat}}(T)$ and for saturation temperature $T_{\text{sat}}(p)$; see Figure 1.

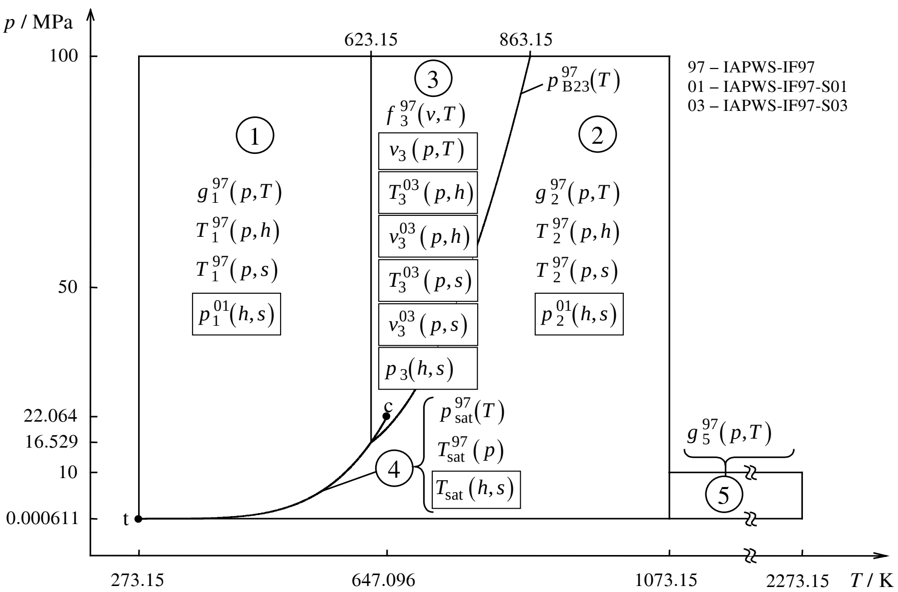

Figure 1. Regions and equations of the IAPWS-IF97, and supplementary backward equations

Using the fundamental equations, all thermodynamic properties can be calculated from given pressure and temperature in regions 1, 2, 5, and from given specific volume and temperature in region 3.

In addition, the IAPWS-IF97 contains backward equations for the most commonly used implicit functions $T(p,h)$ and $T(p,s)$ in regions 1 and 2. Further dependencies have to be calculated iteratively from the fundamental equations. This means that one-dimensional and two-dimensional iterations are necessary in order to determine thermodynamic properties in process modeling. For this purpose, IAPWS has established a task group and first developed backward equations $p(h,s)$ for regions 1 and 2. These equations were adopted as a Supplementary Release in 2001 (IAPWS-IF97-S01).

An international survey revealed that backward equations in region 3 were also required in process modeling. Thus, backward equations for functions $T(p,h)$, $v(p,h)$, $T(p,\mathrm{s})$, $v(p,\mathrm{s})$, and $p(h,s)$ for region 3 have been developed. The equations as functions of (p,h) and (p,s) were adopted by IAPWS as a Supplementary Release in 2003 (IAPWS-IF97-S03). The equations $p(h,s)$ of region 3 have been evaluated successfully and will be adopted as a Supplementary Release in 2004.

In addition, backward equations $v(p,T)$ for region 3 will be proposed in 2004. With the help of these equations, all the thermodynamic properties in region 3 – except a very small region around the critical point – can be calculated from given pressure and temperature without iterations.

For steam-turbine calculations, a backward equation for the saturation temperature as a function of enthalpy and entropy $T_{\mathrm{sat}}(h,s)$ in the wet steam region 4 has been developed.

In order to determine if a given state point is located in the single phase region (region 1, 2, 3) or in the wet steam region (region 4), iterations are necessary for the backward functions of given properties (p,h), (p,s) and (h,s). For this reason, boundary equations $p_{\mathrm{sat}}(h)$ for the functions $T(p,h)$, $v(p,h)$, $p_{\mathrm{sat}}(s)$ for $T(p,\mathrm{s})$, $v(p,\mathrm{s})$, and $h'(s)$, $h''(s)$ for $p(h,s)$ were developed.

In order to enable a determination of the region (1, 2 or 3) from given properties (h,s), equations for the boundary line t = 350 °C between regions 1 and 3 and for the boundary line $p_{\mathrm{B23}}(T)$ were set up.

Finally, using the equations of IAPWS-IF97 and the supplementary backward equations, all thermodynamic properties from given property pairs (p,T), (p,h), (p,s) and (h,s) can be calculated without iterations over the entire range of validity (except region 5) including determination of the region.

The numerical consistencies of the backward and boundary equations are sufficient for most heat-cycle, boiler, and steam-turbine calculations. For users not satisfied with the numerical consistency, the equations are nevertheless still recommended for generating good starting points for an iterative process.

The supplementary backward equations here presented will significantly reduce the computing time for calculating processes with supercritical steam. In particular, the computing time for process calculations which employ functions of enthalpy and entropy will be reduced.