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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

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EXTENDED ABSTRACT

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) [1,2]. 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 $p_{sat}(T)$ and for saturation temperature $T_{sat}(p)$; see Fig. 1. Using the fundamental equations, all thermodynamic properties can be calculated from a given pressure and temperature in regions 1, 2, 5, or from a given specific volume and temperature in region 3.

In addition, the IAPWS-IF97 contains "backward" equations for the most used implicit functions $T(p,h)$ and $T(p,s)$ in regions 1 and 2 for fast calculations in thermodynamic process modeling. Further dependencies must be calculated iteratively from the fundamental equations. Thus, one- and two-dimensional iterations are necessary for determining certain thermodynamic properties in process modeling.

Over the past 6 years, IAPWS has established a task group and developed further backward equations for water and steam supplementing the IAPWS Industrial Formulation 1997. First, backward equations $p(h,s)$ for the liquid and vapor regions were developed and adopted as a supplementary release by IAPWS in 2001 (IAPWS-IF97-S01) [3,4]; see Fig. 1. An international survey of the power industry revealed that backward equations in the critical and supercritical regions were also required in process modeling. Thus the backward equations $T(p,h)$, $v(p,h)$, $T(p,s)$, and $v(p,s)$ were developed for region 3 and adopted as a supplementary release in 2003 and revised in 2004 (IAPWS-IF97-S03rev) [5,6]. Backward equations $p(h,s)$ developed for the critical and supercritical regions were then adopted by IAPWS in 2004 (IAPWS-IF97-S04) [7,8]. This supplementary release also contains a backward equation for the saturation temperature $T_{sat}(h,s)$ in the part of the two-phase region important for steam-turbine calculations. Finally, backward equations $v(p,T)$ for the critical and supercritical regions (region 3) were published in a supplementary release in 2005 (IAPWS-IF97-S05) [9,10]; see Fig. 1.

In order to determine whether a given state point is located in one of the single-phase regions or in the two-phase region, iterations are necessary for the backward functions of the given properties (p,h), (p,s) or (h,s). To avoid these iterations, special region-boundary equations were developed and adopted as a part of the supplementary releases IAPWS-IF97-03rev and IAPWS-IF97-S04.

In conclusion, using the equations of IAPWS-IF97, the supplementary backward equations, and the region-boundary equations, all thermodynamic properties can be calculated without iteration from the input variables (p,T), (p,h), (p,s) and (h,s) in the entire range of validity of IAPWS-IF97, including determination of the region (except for the high-temperature region 5).

The numerical consistencies of the backward and region-boundary equations are sufficient for most heat-cycle, boiler, and steam-turbine calculations. For users not satisfied with the

numerical consistency, the equations are still recommended for generating good starting points for an iterative process.

The supplementary backward equations and the region-boundary equations presented will significantly reduce the computing time for calculating the properties of water and steam [11]. All new backward equations and their use are described comprehensively in [12].

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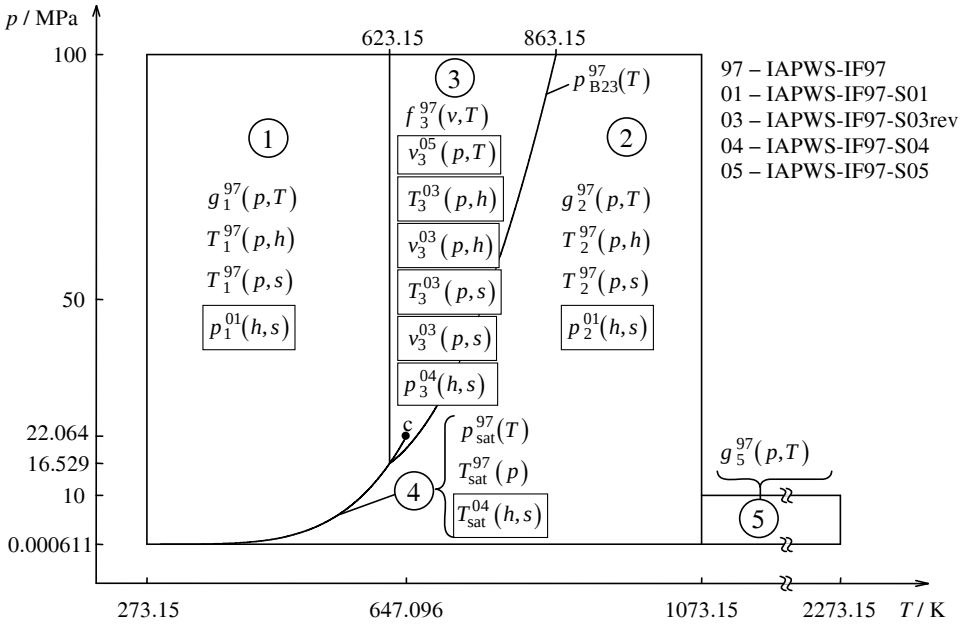

Figure 1. Regions and equations of the IAPWS-IF97, and supplementary backward equations