**The International Association for the Properties of Water and Steam**

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# Revised Supplementary Release on Saturation Properties of Ordinary Water Substance


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This release has been authorized by the International Association for the Properties of Water and Steam (IAPWS) at its meeting in St. Petersburg, Russia, 6 - 12 September 1992, for issue by its Secretariat. The members of IAPWS are Canada, Czechoslovakia, Denmark, the Federal Republic of Germany, France, Japan, Russia, the United Kingdom, and the United States of America.

IAPS previously issued a *Release on the IAPS Formulation 1984 for the Thermodynamic Properties of Ordinary Water Substance for Scientific and General Use* and a *Release on the IAPS Skeleton Tables 1985 for the Thermodynamic Properties of Ordinary Water Substance.* Both releases yield values for the saturation properties of ordinary water substance which are not identical but which agree within the mutual tolerances quoted in the two releases. IAPS also issued a *Supplementary Release on Saturation Properties of Ordinary Water Substance* containing a set of simple equations which yield for ordinary water substance the vapor pressure as well as the density, specific enthalpy and specific entropy of the saturated vapor and liquid. The values calculated from these equations for the vapor pressure, the density and specific enthalpy of the vapor and liquid at saturation are identical to the values tabulated for these properties in the IAPS Skeleton Tables 1985.

This *Supplementary Release on Saturation Properties of Ordinary Water Substance* issued in 1986 was based on the IPTS-68 temperature scale. The temperatures of the triple point, the critical point, and the temperature dependence of all correlation equations presented are known to an accuracy that require parameters to be adjusted for the use of the current Temperature Scale of 1990 (ITS-90). In this revised release the temperature values of the critical point, and the parameters in the correlation equations have been changed to comply with the Temperature Scale of 1990 (ITS-90).

The equations in this revised Supplementary Release have been adjusted to ITS-90 by refitting all equations from the Supplementary Release issued in 1986 to the same input data whose temperature values had been converted to ITS-90 temperatures. Compared to the IPTS-68 temperature values given in the original release, one more decimal place is given here to the converted ITS-90 temperature values. This ensures that any recalculation to the original IPTS-68 temperature values produces the same figures as given in the original source after rounding to the same number of decimal places. This increase by one decimal in the converted ITS-90 temperatures does not imply that these values have been redetermined or are more accurate than previously stated on IPTS-68.

Further details about the equations presented in the release can be found in "International Equations for the Saturation Properties of Ordinary Water Substance – Revised according to the New Temperature Scale of 1990" by W. Wagner and A. Pruß, to be published in the Journal of Physical and Chemical Reference Data.

Further information about this release and other releases issued by IAPWS can be obtained from the Executive Secretary of IAPWS.

# EQUATIONS FOR THE THERMODYNAMIC PROPERTIES OF ORDINARY WATER SUBSTANCE AT SATURATION

## 1. Nomenclature

Thermodynamic quantities:

$h$ = Specific enthalpy
$p$ = Vapor pressure
$s$ = Specific entropy
$T$ = Temperature
$u$ = Specific internal energy
$\rho$ = Density (mass divided by volume)
$\alpha$ = Auxiliary quantity for specific enthalpy
$\phi$ = Auxiliary quantity for specific entropy
$\theta$ = $T/T_c$
$\tau$ = $1-\theta$

Subscripts:

c Denotes value at the critical point
t Denotes value at the (ice I, liquid, vapor) triple point

Superscripts:

' Denotes value of the saturated liquid

" Denotes value of the saturated vapor

Note: $T$ denotes absolute temperature on the International Temperature Scale of 1990.

## 2. Reference constants

$T_c$ = 647.096 K

$p_c$ = 22.064 MPa

$\rho_c$ = 322 kg/m$^3$

$\alpha_0$ = 1000 J/kg

$\phi_0$ = $\alpha_0/T_c$

Note: The numerical values for the critical parameters $p_c$ and $\rho_c$ are identical to those given in *IAPS Statement, 1983, of the Values of the Temperature, Pressure and Density of the Pure Ordinary and Heavy Water Substances at their Respective Critical Points*. The value for $T_c$ corresponds to the IAPS value converted to the current Temperature Scale of 1990 (ITS-90).

## 3. Vapor pressure

$$\ln\left(\frac{p}{p_c}\right) = \frac{T_c}{T}\left[a_1\tau + a_2\tau^{1.5} + a_3\tau^3 + a_4\tau^{3.5} + a_5\tau^4 + a_6\tau^{7.5}\right] \qquad (1)$$

with

$a_1$ = − 7.85951783

$a_2$ = 1.84408259

$a_3$ = − 11.7866497

$a_4$ = 22.6807411

$a_5$ = − 15.9618719

$a_6$ = 1.80122502

## 4. Densities

4.1 Density of the saturated liquid:

$$\frac{\rho'}{\rho_c} = 1 + b_1\tau^{1/3} + b_2\tau^{2/3} + b_3\tau^{5/3} + b_4\tau^{16/3} + b_5\tau^{43/3} + b_6\tau^{110/3} \qquad (2)$$

with

$b_1$ = 1.99274064

$b_2$ = 1.09965342

$b_3$ = − 0.510839303

$b_4$ = − 1.75493479

$b_5$ = − 45.5170352

$b_6$ = − 6.74694450 x 10$^5$

4.2 Density of the saturated vapor:

$$\ln\left(\frac{\rho''}{\rho_c}\right) = c_1\tau^{2/6} + c_2\tau^{4/6} + c_3\tau^{8/6} + c_4\tau^{18/6} + c_5\tau^{37/6} + c_6\tau^{71/6} \tag{3}$$

with

$c_1$ = − 2.03150240 $c_4$ = − 17.2991605
$c_2$ = − 2.68302940 $c_5$ = − 44.7586581
$c_3$ = − 5.38626492 $c_6$ = − 63.9201063

## 5. Specific enthalpy and specific entropy

5.1 Auxiliary equations:

$$\frac{\alpha}{\alpha_0} = d_\alpha + d_1\theta^{-19} + d_2\theta + d_3\theta^{4.5} + d_4\theta^5 + d_5\theta^{54.5} \tag{4}$$

$$\frac{\phi}{\phi_0} = d_\phi + \frac{19}{20}d_1\theta^{-20} + d_2\ln\theta + \frac{9}{7}d_3\theta^{3.5} + \frac{5}{4}d_4\theta^4 + \frac{109}{107}d_5\theta^{53.5} \tag{5}$$

with

$d_1$ = − 5.65134998 x $10^{-8}$ $d_\alpha$ = − 1135.905627715
$d_2$ = 2690.66631 $d_\phi$ = 2319.5246
$d_3$ = 127.287297
$d_4$ = − 135.003439
$d_5$ = 0.981825814

5.2 Specific enthalpy of the saturated liquid:

$$h' = \alpha + \frac{T}{\rho'}\frac{\mathrm{d}p}{\mathrm{d}T} \tag{6}$$

Eq. (6) yields the specific enthalpy of the saturated liquid when used in conjunction with Eqs. (1), (2), and (4).

Note: The specific internal energy and the specific entropy of the liquid at the triple point $u'_t$ and $s'_t$ have been set equal to zero (5th ICPS 1956). As a consequence, from the relation $h'_t = p_s(T_t)/\rho'(T_t)$ one gets for the specific enthalpy of the liquid at the triple point has the value

$$h'_t = 0.611786 \text{ J/kg}.$$

In order to reproduce this numerical value for $h'_t$ from Eq. (6), 13 significant figures are required for the constant $d_\alpha$ as quoted above. A decrease of the number of decimal places in $d_\alpha$ affects the enthalpy of the saturated liquid only near the triple point, but does not significantly affect the values of $p$, $\rho'$, $\rho''$, $h''$, $s'$ and $s''$. For example, a reduction of $d_\alpha$ to 10 significant figures changes $h'/(\text{J/kg})$ in the 4th decimal place at a temperature of 273.16 K.

5.3 Specific enthalpy of the saturated vapor:

$$h'' = \alpha + \frac{T}{\rho''}\frac{\mathrm{d}p}{\mathrm{d}T} \tag{7}$$

Eq. (7) yields the specific enthalpy of the saturated vapor when used in conjunction with Eqs. (1), (3), and (4).

5.4 Specific entropy of the saturated liquid:

$$s' = \phi + \frac{1}{\rho'}\frac{\mathrm{d}p}{\mathrm{d}T} \tag{8}$$

Eq. (8) yields the specific entropy of the saturated liquid when used in conjunction with Eqs. (1), (2), and (5).

5.5 Specific entropy of the saturated vapor:

$$s'' = \phi + \frac{1}{\rho''}\frac{\mathrm{d}p}{\mathrm{d}T} \tag{9}$$

Eq. (9) yields the specific entropy of the saturated vapor when used in conjunction with Eqs. (1), (3), and (5).

## 6. Range of validity of the equations

IAPWS endorses the validity of the equations presented in this revised supplementary release for vapor-liquid equilibrium from the triple point to the critical point. This corresponds to

$$273.16 \text{ K} \leq T \leq 647.096 \text{ K} \tag{10}$$

## 7. Estimates of uncertainty

Values calculated from the equations for $p$, $1/\rho'$, $1/\rho''$, $h'$, and $h''$ have estimated uncertainties which are identical to the values in Table 3 of the *Release on the IAPS Skeleton Tables 1985 for the Thermodynamic Properties of Ordinary Water Substance.* The values calculated from the equation for $p$, $1/\rho'$, $1/\rho''$, $h'$, and $h''$ together with their estimated uncertainties are identical to values in Table 3 of the forthcoming *Revised Release on the IAPWS Skeleton Tables 1985 for the Thermodynamic Properties of Ordinary Water Substance.*

## 8. Computer-program verification

To assist the user in computer-program verification, Table 1 lists values for $p$, $dp/dT$, $\rho'$, $\rho''$, $\alpha$, $h'$, $h''$, $\phi$, $s'$ and $s''$ calculated at three temperatures. The results quoted in Table 1 were obtained with the aid of a computer having 14 significant figure accuracy and with the values of $d_\alpha$ and $d_\phi$ given in Section 5.1. If the calculations are performed with a computer with less than 14 significant figures, the results will be clearly within the estimated uncertainty of the various properties except for the enthalpy of the saturated liquid close to the triple point.

Table 1. Thermodynamic property values calculated at three selected temperatures

| | $T$ = 273.16 K | $T$ = 373.1243 K | $T$ = 647.096 |
|---|---|---|---|
| $p$/Pa | 611.657 | 0.101325 x $10^6$ | 22.064 x $10^6$ |
| $(dp/dT)/(Pa\ K^{-1})$ | 44.436693 | 3.616 x $10^3$ | 268 x $10^3$ |
| $\rho'/(kg\ m^{-3})$ | 999.789 | 958.365 | 322 |
| $\rho''/(kg\ m^{-3})$ | 0.00485426 | 0.597586 | 322 |
| $\alpha/(J\ kg^{-1})$ | −11.529101 | 417.65 x $10^3$ | 1548 x $10^3$ |
| $h'/(J\ kg^{-1})$ | 0.611786 | 419.05 x $10^3$ | 2086.6 x $10^3$ |
| $h''/(J\ kg^{-1})$ | 2500.5 x $10^3$ | 2675.7 x $10^3$ | 2086.6 x $10^3$ |
| $\phi/(J\ kg^{-1}K^{-1})$ | − 0.04 | 1.303 x $10^3$ | 3.578 x $10^3$ |
| $s'/(J\ kg^{-1}K^{-1})$ | 0 | 1.307 x $10^3$ | 4.410 x $10^3$ |
| $s''/(J\ kg^{-1}K^{-1})$ | 9.154 x $10^3$ | 7.355 x $10^3$ | 4.410 x $10^3$ |