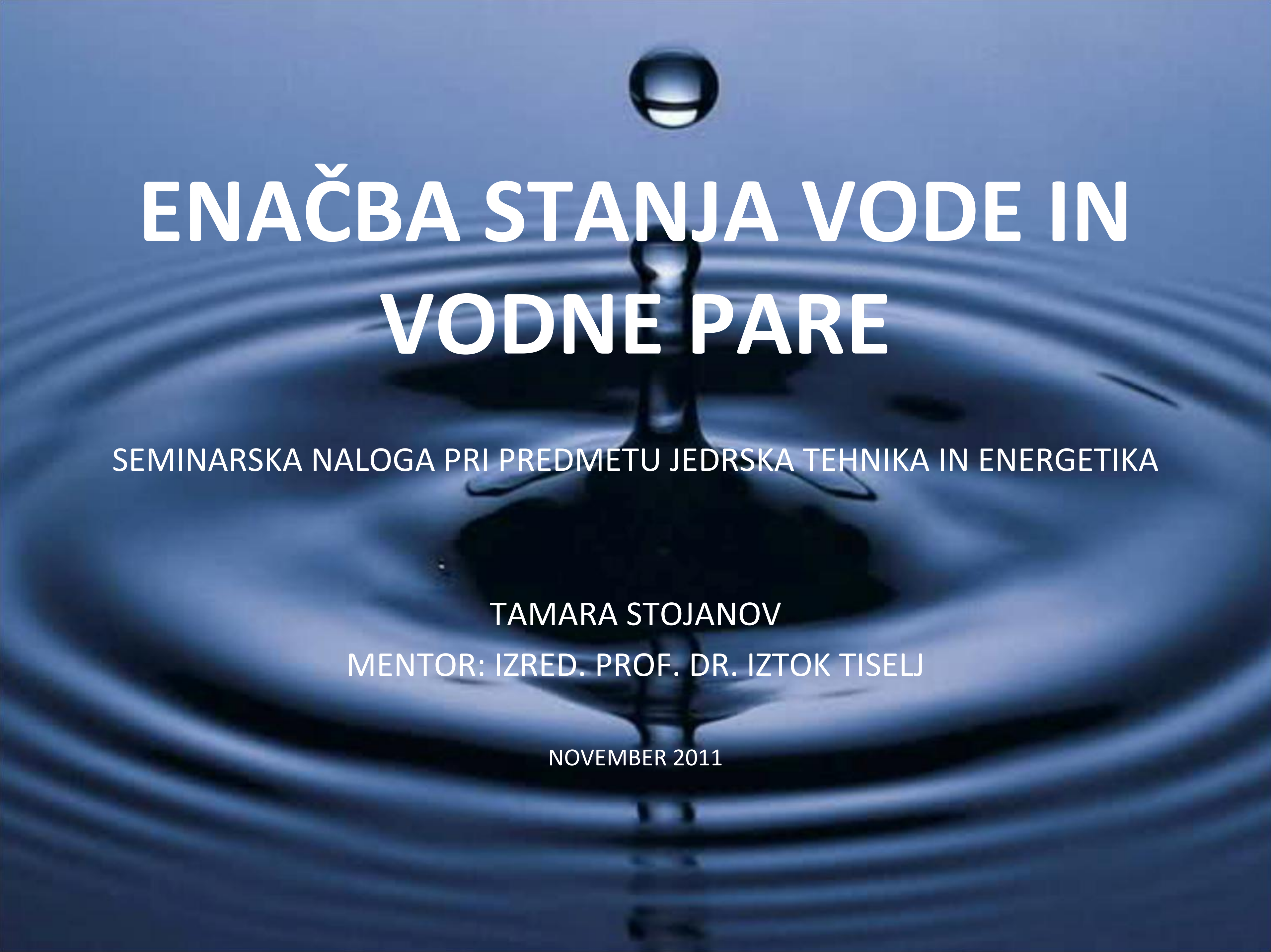

ENAČBA STANJA VODE IN VODNE PARE

SEMINARSKA NALOGA PRI PREDMETU JEDRSKA TEHNIKA IN ENERGETIKA

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Enačba stanja

- idealni plin: $pV = \frac{m}{M} RT$

  p tlak, *V* prostornina, *m* masa, *M* molska masa, *R* splošna plinska konstanta, *T* temperatura
- Van der Waalsova: $\left(p + \frac{a}{V_M{}^2}\right)\left(V_M - b\right) = RT$ - približek

  V_M volumen mola snovi, *a, b* konstanti, značilni za snov
- natančnost
- točnost ob kritični točki
- točnost ob faznih prehodih
- točnost v ekstremnih pogojih (*T, p*)

Pomembnost H_2O

- energetika (HE, pogon turbin, hladilo)
- industrija
- topilo
- vreme, klima
- geologija
- živa bitja
- …

http://www.flickr.com/photos/vattenfall/3581340677/sizes/m/in/photostream/

Preučevanje lastnosti H_2O

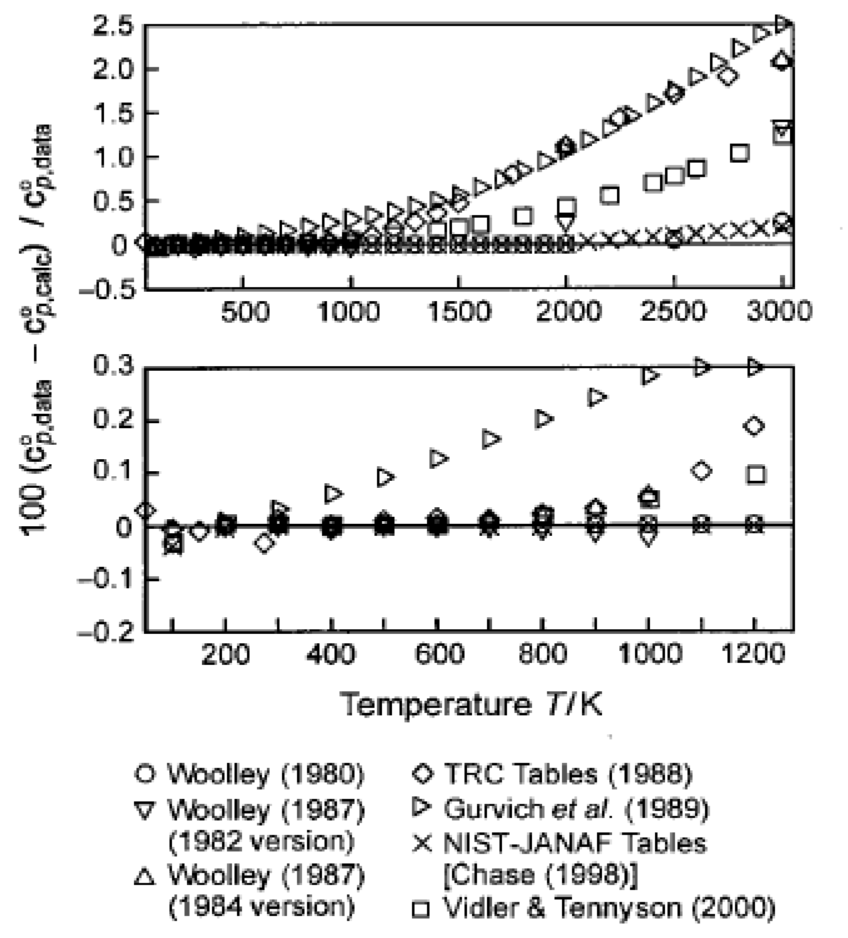
- IAPWS - International Association for the Properties of Water and Steam
- izmerjeni podatki => enačba stanja

http://www.iapws.org/

- IAPWS-95 (The IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use)
- IAPWS-IF97 (The IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam)
- računalniški programi (npr. http://webbook.nist.gov/chemistry/fluid/)
- parne tabele
- od tališča do 1273 K, do 1000 MPa, tudi do 0,0001 % natančno

Eksperimentalni podatki

- izbrani izmed 20 000 podatkov, merjenih od l. 1928 dalje
- natančnost
- konsistenca z ostalimi podatki



Eksperimentalni podatki

- po celem območju

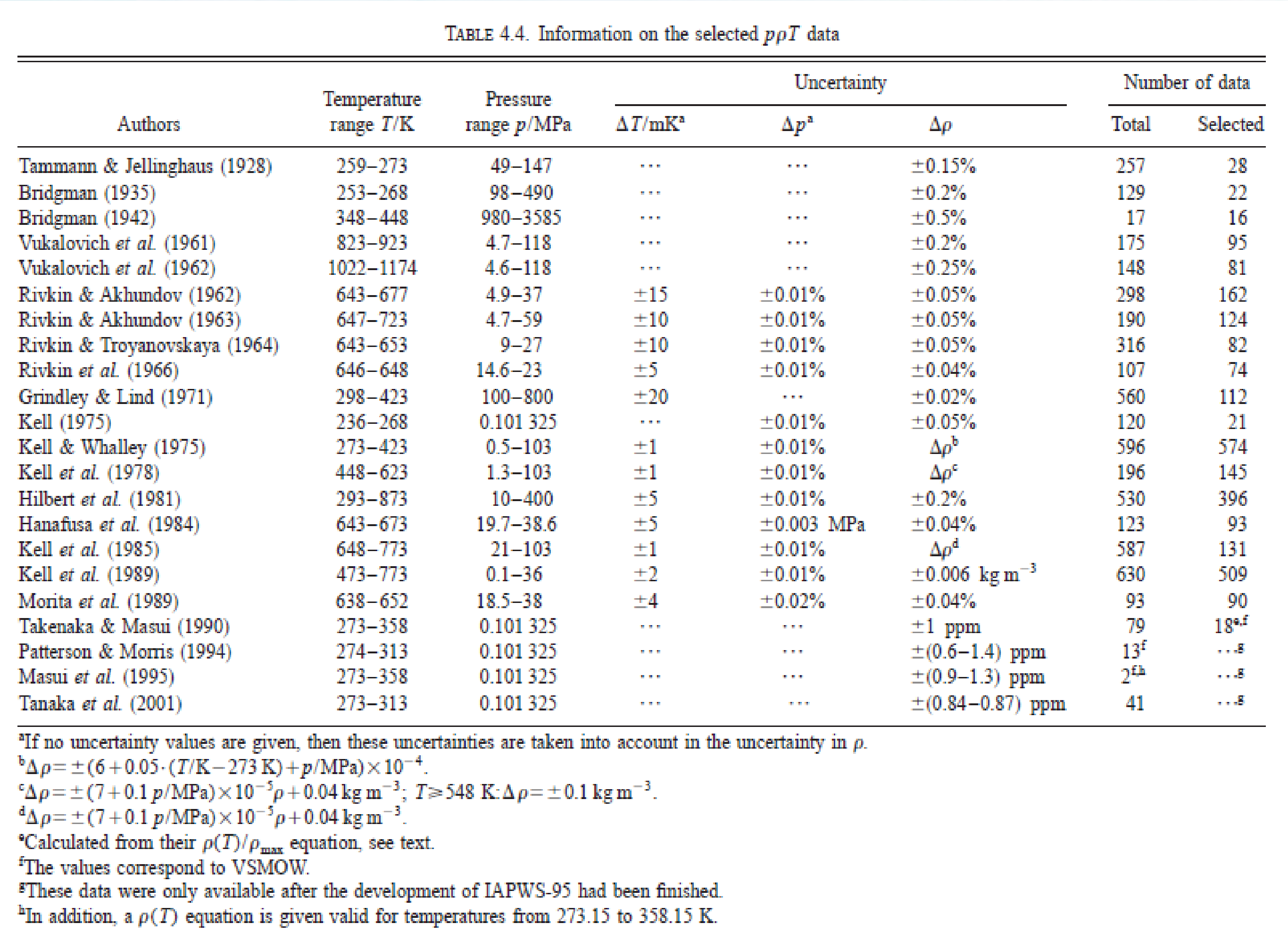


TABLE 4.4. Information on the selected $p\rho T$ data

Authors	Temperature range T/K	Pressure range p/MPa	Uncertainty			Number of data	
			ΔT/mK^{a}	Δp^{a}	$\Delta\rho$	Total	Selected
Tammann & Jellinghaus (1928)	259–273	49–147	⋯	⋯	±0.15%	257	28
Bridgman (1935)	253–268	98–490	⋯	⋯	±0.2%	129	22
Bridgman (1942)	348–448	980–3585	⋯	⋯	±0.5%	17	16
Vukalovich *et al.* (1961)	823–923	4.7–118	⋯	⋯	±0.2%	175	95
Vukalovich *et al.* (1962)	1022–1174	4.6–118	⋯	⋯	±0.25%	148	81
Rivkin & Akhundov (1962)	643–677	4.9–37	±15	±0.01%	±0.05%	298	162
Rivkin & Akhundov (1963)	647–723	4.7–59	±10	±0.01%	±0.05%	190	124
Rivkin & Troyanovskaya (1964)	643–653	9–27	±10	±0.01%	±0.05%	316	82
Rivkin *et al.* (1966)	646–648	14.6–23	±5	±0.01%	±0.04%	107	74
Grindley & Lind (1971)	298–423	100–800	±20	⋯	±0.02%	560	112
Kell (1975)	236–268	0.101 325	⋯	±0.01%	±0.05%	120	21
Kell & Whalley (1975)	273–423	0.5–103	±1	±0.01%	$\Delta\rho^{b}$	596	574
Kell *et al.* (1978)	448–623	1.3–103	±1	±0.01%	$\Delta\rho^{c}$	196	145
Hilbert *et al.* (1981)	293–873	10–400	±5	±0.01%	±0.2%	530	396
Hanafusa *et al.* (1984)	643–673	19.7–38.6	±5	±0.003 MPa	±0.04%	123	93
Kell *et al.* (1985)	648–773	21–103	±1	±0.01%	$\Delta\rho^{d}$	587	131
Kell *et al.* (1989)	473–773	0.1–36	±2	±0.01%	±0.006 kg m^{-3}	630	509
Morita *et al.* (1989)	638–652	18.5–38	±4	±0.02%	±0.04%	93	90
Takenaka & Masui (1990)	273–358	0.101 325	⋯	⋯	±1 ppm	79	18^{e,f}
Patterson & Morris (1994)	274–313	0.101 325	⋯	⋯	±(0.6–1.4) ppm	13^{f}	⋯^{g}
Masui *et al.* (1995)	273–358	0.101 325	⋯	⋯	±(0.9–1.3) ppm	2^{f,h}	⋯^{g}
Tanaka *et al.* (2001)	273–313	0.101 325	⋯	⋯	±(0.84–0.87) ppm	41	⋯^{g}

[a] If no uncertainty values are given, then these uncertainties are taken into account in the uncertainty in ρ.

[b] $\Delta\rho=\pm(6+0.05\cdot(T/\mathrm{K}-273\ \mathrm{K})+p/\mathrm{MPa})\times10^{-4}$.

[c] $\Delta\rho=\pm(7+0.1\,p/\mathrm{MPa})\times10^{-5}\rho+0.04\ \mathrm{kg\,m^{-3}}$; $T\geqslant548\ \mathrm{K}$: $\Delta\rho=\pm0.1\ \mathrm{kg\,m^{-3}}$.

[d] $\Delta\rho=\pm(7+0.1\,p/\mathrm{MPa})\times10^{-5}\rho+0.04\ \mathrm{kg\,m^{-3}}$.

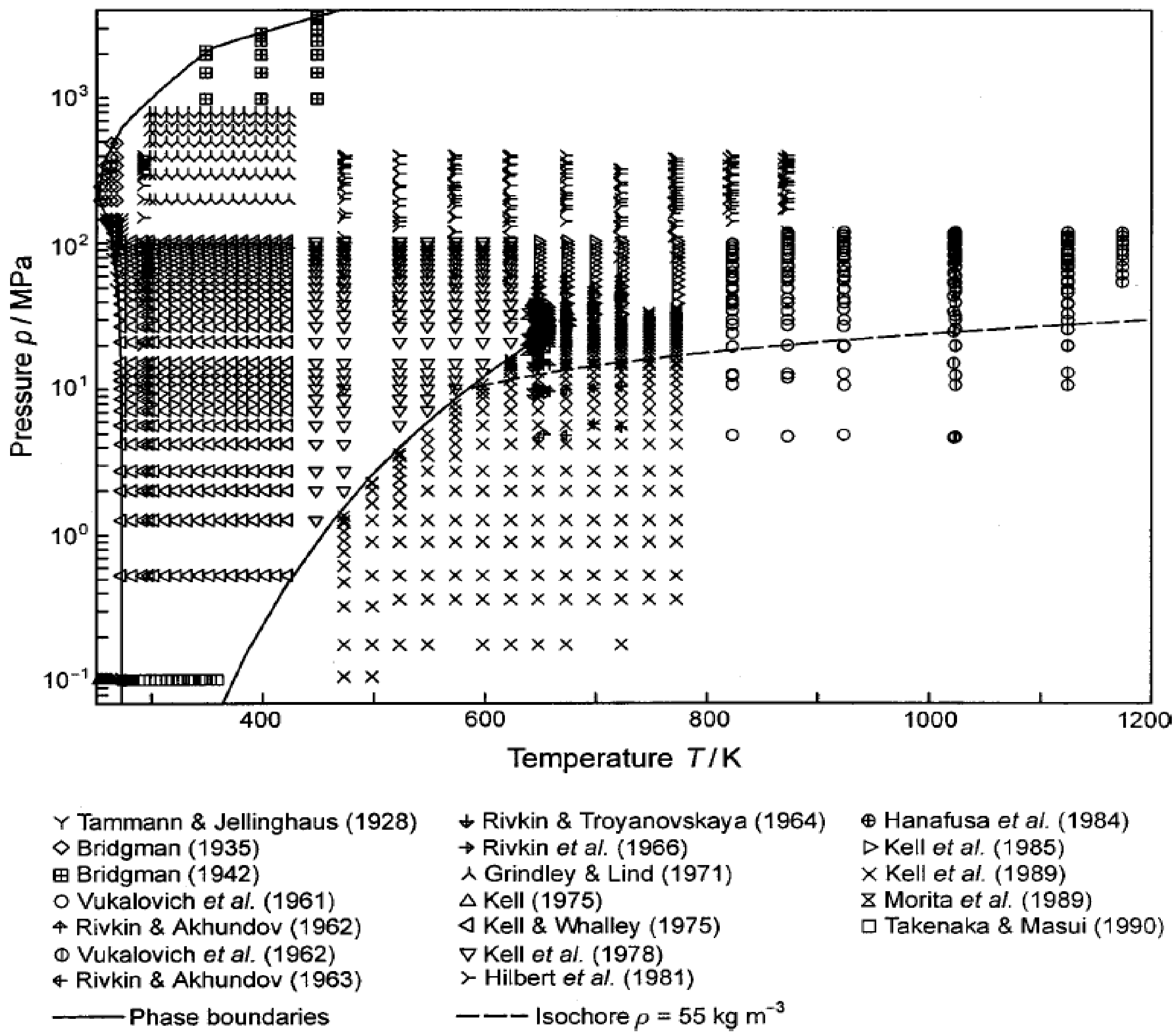
[e] Calculated from their $\rho(T)/\rho_{\mathrm{max}}$ equation, see text.

[f] The values correspond to VSMOW.

[g] These data were only available after the development of IAPWS-95 had been finished.

[h] In addition, a $\rho(T)$ equation is given valid for temperatures from 273.15 to 358.15 K.

Eksperimentalni podatki

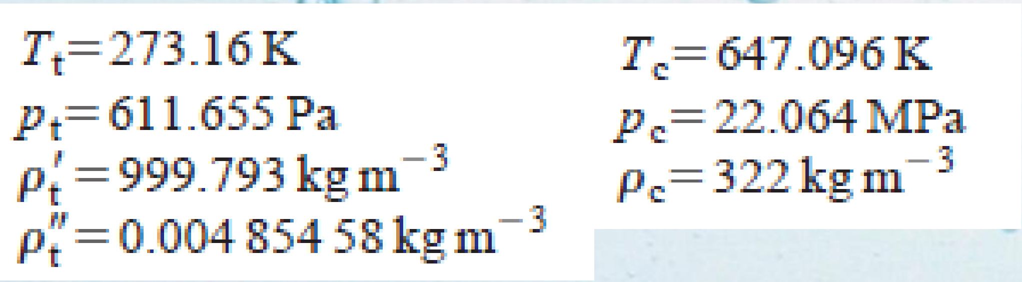


Eksperimentalni podatki

- temperaturna lestvica ITS-90
- če ni meritev/ni mogoče meriti, izračunamo sintetične podatke
- če imamo meritve za količino preko območja, lahko testiramo kvaliteto ekstrapolacije

Krivulja nasičenja

- trojna točka
- kritična točka



$T_t = 273.16\,\mathrm{K}$

$p_t = 611.655\,\mathrm{Pa}$

$\rho_t' = 999.793\,\mathrm{kg\,m^{-3}}$

$\rho_t'' = 0.004\,854\,58\,\mathrm{kg\,m^{-3}}$

$T_c = 647.096\,\mathrm{K}$

$p_c = 22.064\,\mathrm{MPa}$

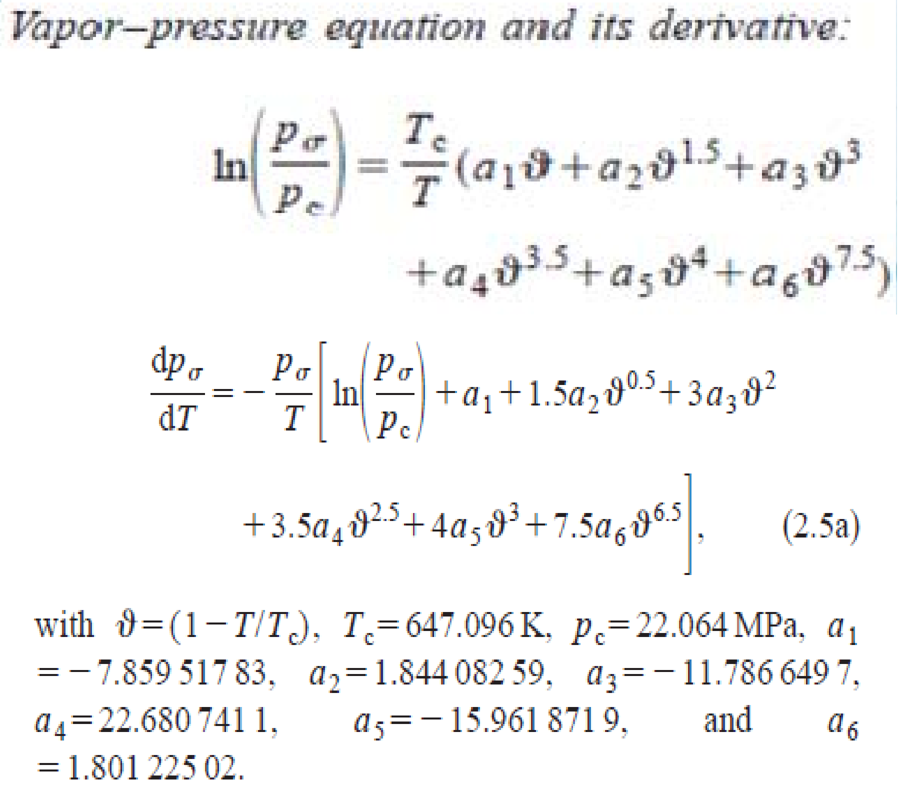
$\rho_c = 322\,\mathrm{kg\,m^{-3}}$

ρ’ gostota kapljevine, *ρ’’* gostota pare

- poznamo enačbe
- veljajo le v bližini faznega prehoda
- eksperimentalno določeni koeficienti

Krivulja nasičenja

- tlak pare, gostota kapljevine in pare:

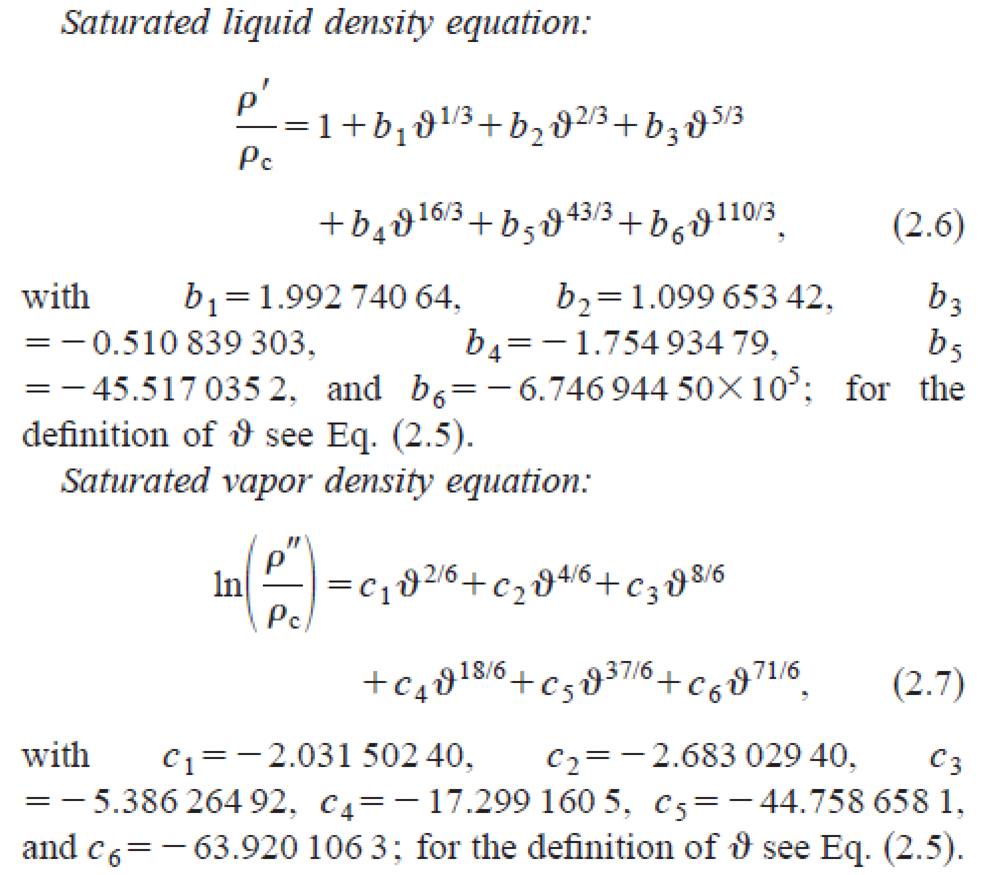


Vapor–pressure equation and its derivative:

$$\ln\left(\frac{p_\sigma}{p_c}\right)=\frac{T_c}{T}(a_1\vartheta+a_2\vartheta^{1.5}+a_3\vartheta^3+a_4\vartheta^{3.5}+a_5\vartheta^4+a_6\vartheta^{7.5})$$

$$\frac{dp_\sigma}{dT}=-\frac{p_\sigma}{T}\left[\ln\left(\frac{p_\sigma}{p_c}\right)+a_1+1.5a_2\vartheta^{0.5}+3a_3\vartheta^2+3.5a_4\vartheta^{2.5}+4a_5\vartheta^3+7.5a_6\vartheta^{6.5}\right], \qquad (2.5a)$$

with $\vartheta=(1-T/T_c)$, $T_c=647.096\,\mathrm{K}$, $p_c=22.064\,\mathrm{MPa}$, $a_1=-7.859\,517\,83$, $a_2=1.844\,082\,59$, $a_3=-11.786\,649\,7$, $a_4=22.680\,741\,1$, $a_5=-15.961\,871\,9$, and $a_6=1.801\,225\,02$.



Saturated liquid density equation:

$$\frac{\rho'}{\rho_c}=1+b_1\vartheta^{1/3}+b_2\vartheta^{2/3}+b_3\vartheta^{5/3}+b_4\vartheta^{16/3}+b_5\vartheta^{43/3}+b_6\vartheta^{110/3}, \qquad (2.6)$$

with $b_1=1.992\,740\,64$, $b_2=1.099\,653\,42$, $b_3=-0.510\,839\,303$, $b_4=-1.754\,934\,79$, $b_5=-45.517\,035\,2$, and $b_6=-6.746\,944\,50\times10^5$; for the definition of ϑ see Eq. (2.5).

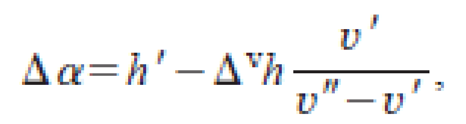
Saturated vapor density equation:

$$\ln\left(\frac{\rho''}{\rho_c}\right)=c_1\vartheta^{2/6}+c_2\vartheta^{4/6}+c_3\vartheta^{8/6}+c_4\vartheta^{18/6}+c_5\vartheta^{37/6}+c_6\vartheta^{71/6}, \qquad (2.7)$$

with $c_1=-2.031\,502\,40$, $c_2=-2.683\,029\,40$, $c_3=-5.386\,264\,92$, $c_4=-17.299\,160\,5$, $c_5=-44.758\,658\,1$, and $c_6=-63.920\,106\,3$; for the definition of ϑ see Eq. (2.5).

Krivulja nasičenja

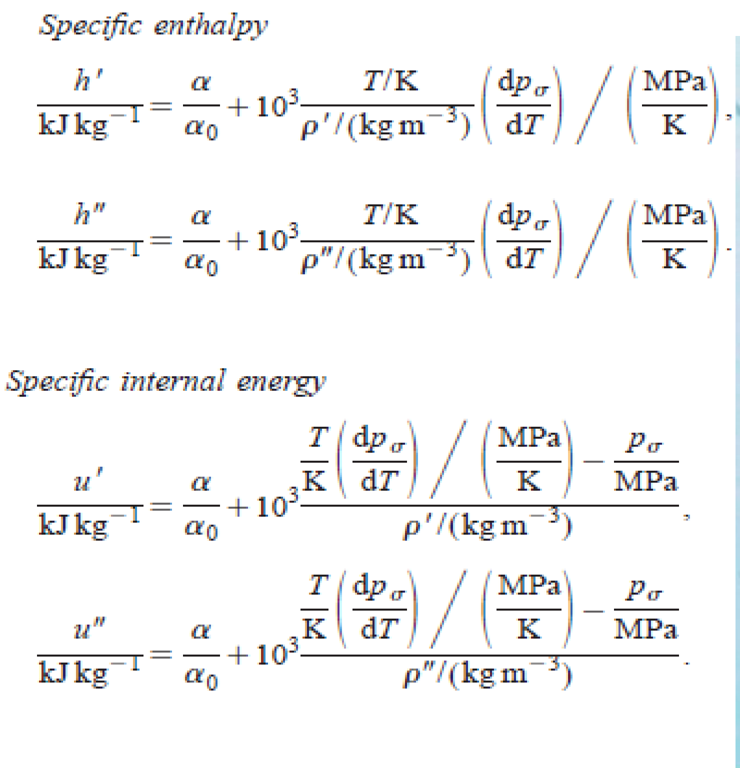
- razlika notranje energije pri različnih temperaturah (Δα), specifične entalpija (*h*), notranja energija (*u*), entropija (*s*)



$$\Delta\alpha = h' - \Delta^{\mathrm{v}}h\,\frac{v'}{v''-v'},$$

v specifični volumen

$\Delta^{\mathrm{v}}h$ izparilna toplota



Specific enthalpy

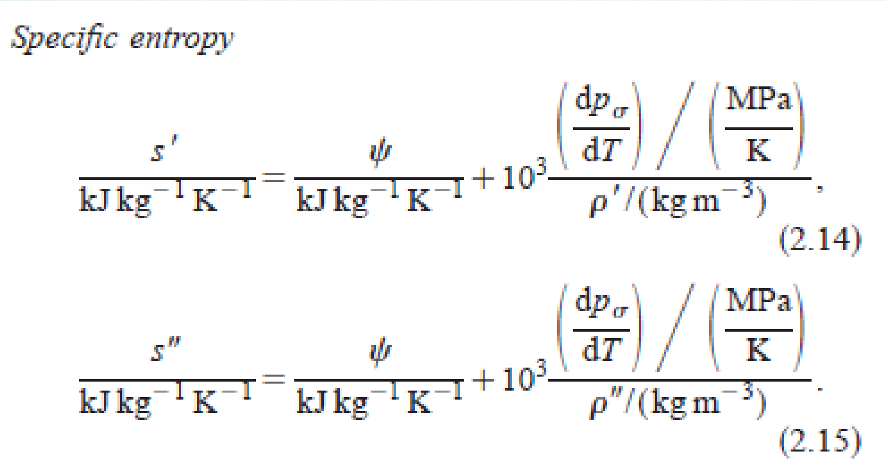
$$\frac{h'}{\mathrm{kJ\,kg^{-1}}} = \frac{\alpha}{\alpha_0} + 10^3 \frac{T/\mathrm{K}}{\rho'/(\mathrm{kg\,m^{-3}})} \left(\frac{\mathrm{d}p_\sigma}{\mathrm{d}T}\right) \Big/ \left(\frac{\mathrm{MPa}}{\mathrm{K}}\right),$$

$$\frac{h''}{\mathrm{kJ\,kg^{-1}}} = \frac{\alpha}{\alpha_0} + 10^3 \frac{T/\mathrm{K}}{\rho''/(\mathrm{kg\,m^{-3}})} \left(\frac{\mathrm{d}p_\sigma}{\mathrm{d}T}\right) \Big/ \left(\frac{\mathrm{MPa}}{\mathrm{K}}\right).$$

Specific internal energy

$$\frac{u'}{\mathrm{kJ\,kg^{-1}}} = \frac{\alpha}{\alpha_0} + 10^3 \frac{\frac{T}{\mathrm{K}}\left(\frac{\mathrm{d}p_\sigma}{\mathrm{d}T}\right) \Big/ \left(\frac{\mathrm{MPa}}{\mathrm{K}}\right) - \frac{p_\sigma}{\mathrm{MPa}}}{\rho'/(\mathrm{kg\,m^{-3}})},$$

$$\frac{u''}{\mathrm{kJ\,kg^{-1}}} = \frac{\alpha}{\alpha_0} + 10^3 \frac{\frac{T}{\mathrm{K}}\left(\frac{\mathrm{d}p_\sigma}{\mathrm{d}T}\right) \Big/ \left(\frac{\mathrm{MPa}}{\mathrm{K}}\right) - \frac{p_\sigma}{\mathrm{MPa}}}{\rho''/(\mathrm{kg\,m^{-3}})}.$$



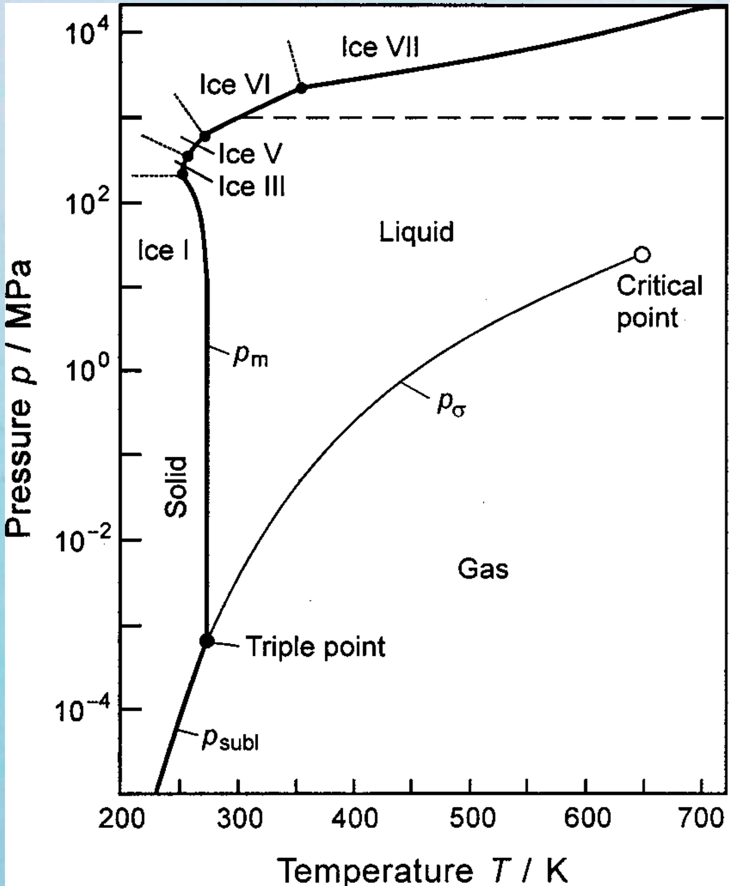
Specific entropy

$$\frac{s'}{\mathrm{kJ\,kg^{-1}\,K^{-1}}} = \frac{\psi}{\mathrm{kJ\,kg^{-1}\,K^{-1}}} + 10^3 \frac{\left(\frac{\mathrm{d}p_\sigma}{\mathrm{d}T}\right) \Big/ \left(\frac{\mathrm{MPa}}{\mathrm{K}}\right)}{\rho'/(\mathrm{kg\,m^{-3}})}, \tag{2.14}$$

$$\frac{s''}{\mathrm{kJ\,kg^{-1}\,K^{-1}}} = \frac{\psi}{\mathrm{kJ\,kg^{-1}\,K^{-1}}} + 10^3 \frac{\left(\frac{\mathrm{d}p_\sigma}{\mathrm{d}T}\right) \Big/ \left(\frac{\mathrm{MPa}}{\mathrm{K}}\right)}{\rho''/(\mathrm{kg\,m^{-3}})}. \tag{2.15}$$

Krivulja nasičenja

- prehod led – voda ni vključen v IAPSW-95
- voda tvori 5 različnih struktur leda, le ena lahko sublimira



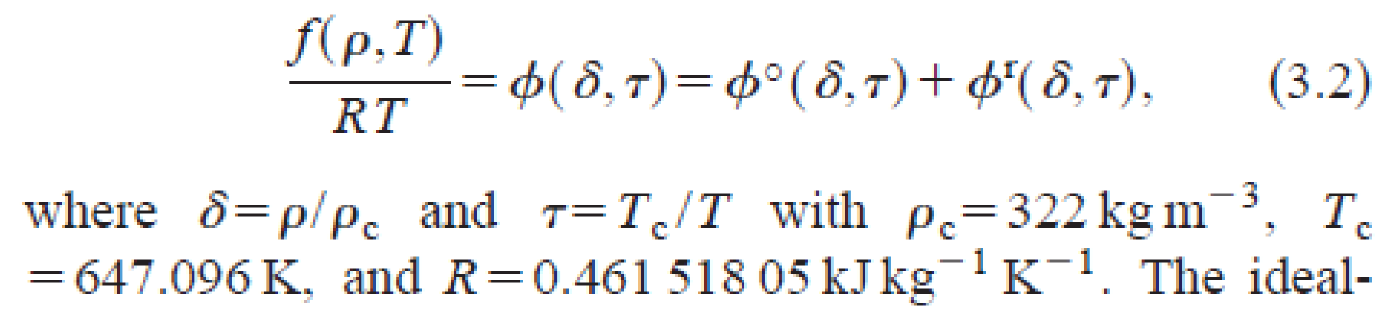
$$\ln\left(\frac{p_{\text{subl}}}{p_{\text{n}}}\right) = -13.928\,169(1-\theta^{-1.5}) + 34.707\,823\,8(1-\theta^{-1.25}), \qquad (2.21)$$

with $\theta = T/T_{\text{n}}$, $T_{\text{n}} = 273.16\,\text{K}$, and $p_{\text{n}} = 0.000\,611\,657\,\text{MPa}$.

Plinska enačba

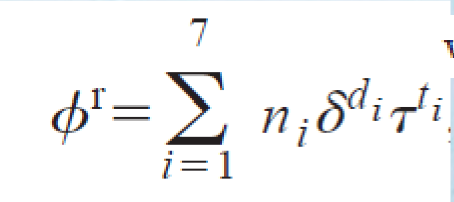
- izhodišče, ker se jo da delno razširiti na tekočo fazo
- tlak, temperatura, gostota, hitrost zvoka, specifična izobarna toplota, Joule-Kelvinov koeficient, … - upošteva čez 1200 meritev
- velja med 273 in 1273 K ter do gostot 55 kg/m^3

Plinska enačba



$$\frac{f(\rho,T)}{RT}=\phi(\delta,\tau)=\phi^\circ(\delta,\tau)+\phi^r(\delta,\tau), \qquad (3.2)$$

where $\delta=\rho/\rho_c$ and $\tau=T_c/T$ with $\rho_c=322\,\mathrm{kg\,m^{-3}}$, $T_c=647.096\,\mathrm{K}$, and $R=0.461\,518\,05\,\mathrm{kJ\,kg^{-1}\,K^{-1}}$. The ideal-



$$\phi^r=\sum_{i=1}^{7} n_i\delta^{d_i}\tau^{t_i}$$

where $\delta=\rho/\rho_c$ and $\tau=T_c/T$ with $\rho_c=322\,\mathrm{kg\,m^{-3}}$

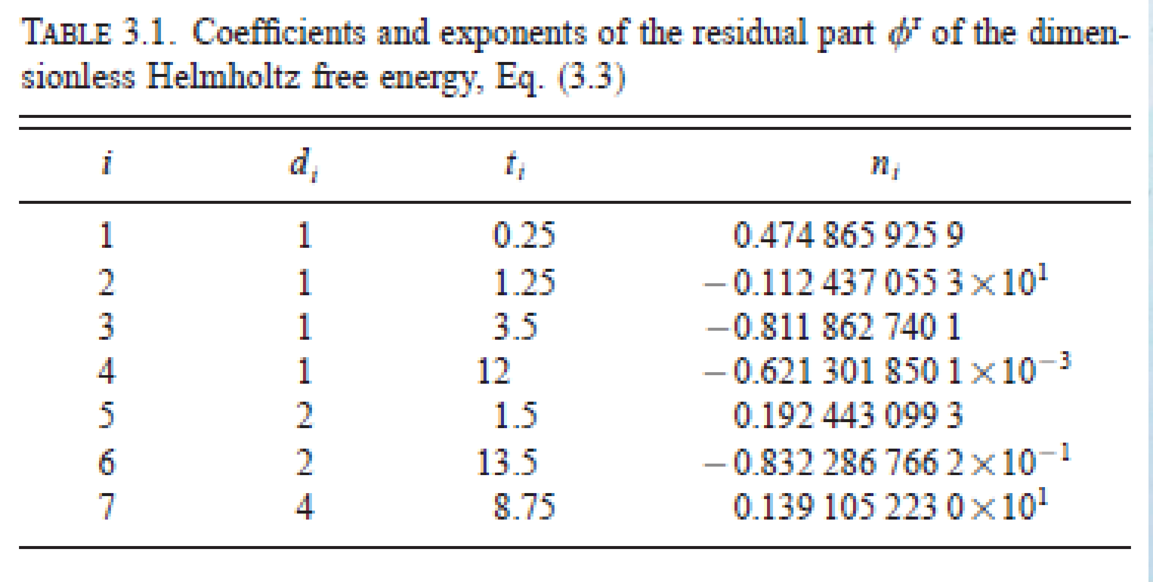
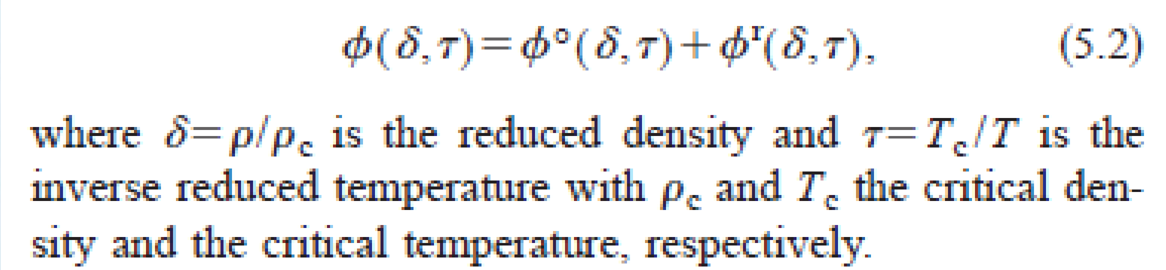


TABLE 3.1. Coefficients and exponents of the residual part ϕ^r of the dimensionless Helmholtz free energy, Eq. (3.3)

i	d_i	t_i	n_i
1	1	0.25	0.474 865 925 9
2	1	1.25	$-0.112\,437\,055\,3\times10^{1}$
3	1	3.5	$-0.811\,862\,740\,1$
4	1	12	$-0.621\,301\,850\,1\times10^{-3}$
5	2	1.5	0.192 443 099 3
6	2	13.5	$-0.832\,286\,766\,2\times10^{-1}$
7	4	8.75	$0.139\,105\,223\,0\times10^{1}$

Razvoj formulacije

- iščemo: 
  $f(\rho,T)=f^{\circ}(\rho,T)+f^{\mathrm{r}}(\rho,T)$
- brezdimenzijsko (delimo z R*T*):



$$\phi(\delta,\tau)=\phi^{\circ}(\delta,\tau)+\phi^{\mathrm{r}}(\delta,\tau), \qquad (5.2)$$

where $\delta=\rho/\rho_{\mathrm{c}}$ is the reduced density and $\tau=T_{\mathrm{c}}/T$ is the inverse reduced temperature with ρ_{c} and T_{c} the critical density and the critical temperature, respectively.

- prvi del za idealni plin, drugi del preostali efekti
- vse ostale količine se dajo izračunati iz tega

Razvoj formulacije

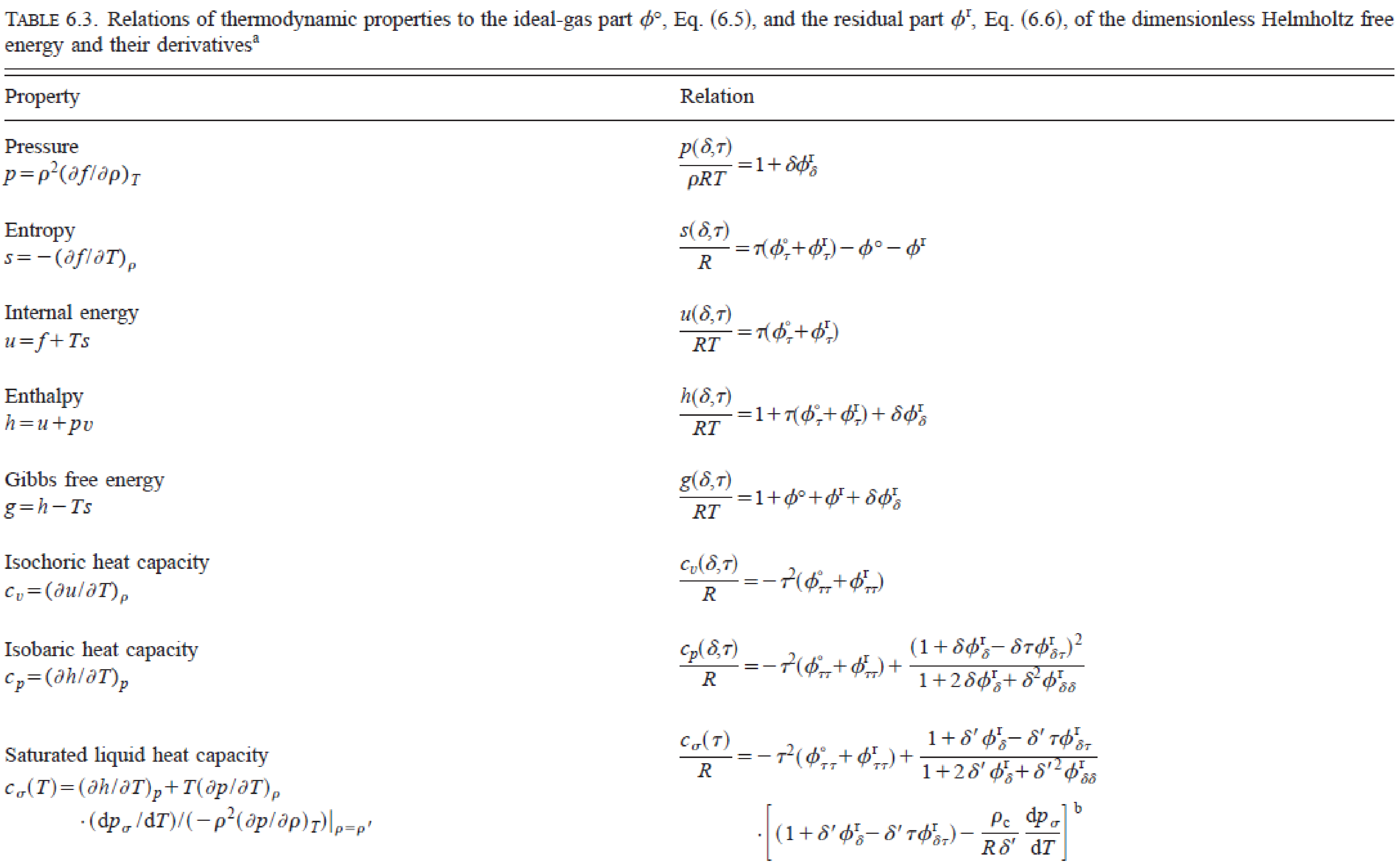


TABLE 6.3. Relations of thermodynamic properties to the ideal-gas part ϕ°, Eq. (6.5), and the residual part ϕ^r, Eq. (6.6), of the dimensionless Helmholtz free energy and their derivatives[a]

Property	Relation
Pressure $p=\rho^2(\partial f/\partial \rho)_T$	$\frac{p(\delta,\tau)}{\rho RT}=1+\delta\phi^\mathrm{r}_\delta$
Entropy $s=-(\partial f/\partial T)_\rho$	$\frac{s(\delta,\tau)}{R}=\tau(\phi^\circ_\tau+\phi^\mathrm{r}_\tau)-\phi^\circ-\phi^\mathrm{r}$
Internal energy $u=f+Ts$	$\frac{u(\delta,\tau)}{RT}=\tau(\phi^\circ_\tau+\phi^\mathrm{r}_\tau)$
Enthalpy $h=u+pv$	$\frac{h(\delta,\tau)}{RT}=1+\tau(\phi^\circ_\tau+\phi^\mathrm{r}_\tau)+\delta\phi^\mathrm{r}_\delta$
Gibbs free energy $g=h-Ts$	$\frac{g(\delta,\tau)}{RT}=1+\phi^\circ+\phi^\mathrm{r}+\delta\phi^\mathrm{r}_\delta$
Isochoric heat capacity $c_v=(\partial u/\partial T)_\rho$	$\frac{c_v(\delta,\tau)}{R}=-\tau^2(\phi^\circ_{\tau\tau}+\phi^\mathrm{r}_{\tau\tau})$
Isobaric heat capacity $c_p=(\partial h/\partial T)_p$	$\frac{c_p(\delta,\tau)}{R}=-\tau^2(\phi^\circ_{\tau\tau}+\phi^\mathrm{r}_{\tau\tau})+\frac{(1+\delta\phi^\mathrm{r}_\delta-\delta\tau\phi^\mathrm{r}_{\delta\tau})^2}{1+2\delta\phi^\mathrm{r}_\delta+\delta^2\phi^\mathrm{r}_{\delta\delta}}$
Saturated liquid heat capacity $c_\sigma(T)=(\partial h/\partial T)_p+T(\partial p/\partial T)_\rho$ $\cdot(\mathrm{d}p_\sigma/\mathrm{d}T)/(-\rho^2(\partial p/\partial \rho)_T)\vert_{\rho=\rho'}$	$\frac{c_\sigma(\tau)}{R}=-\tau^2(\phi^\circ_{\tau\tau}+\phi^\mathrm{r}_{\tau\tau})+\frac{1+\delta'\phi^\mathrm{r}_\delta-\delta'\tau\phi^\mathrm{r}_{\delta\tau}}{1+2\delta'\phi^\mathrm{r}_\delta+\delta'^2\phi^\mathrm{r}_{\delta\delta}}$ $\cdot\left[(1+\delta'\phi^\mathrm{r}_\delta-\delta'\tau\phi^\mathrm{r}_{\delta\tau})-\frac{\rho_\mathrm{c}}{R\delta'}\frac{\mathrm{d}p_\sigma}{\mathrm{d}T}\right]^\mathrm{b}$

Razvoj formulacije

Speed of sound $w=(\partial p/\partial \rho)_s^{1/2}$	$\frac{w^2(\delta,\tau)}{RT}=1+2\delta\phi^r_\delta+\delta^2\phi^r_{\delta\delta}-\frac{(1+\delta\phi^r_\delta-\delta\tau\phi^r_{\delta\tau})^2}{\tau^2(\phi^\circ_{\tau\tau}+\phi^r_{\tau\tau})}$
Joule–Thomson coefficient $\mu=(\partial T/\partial p)_h$	$\mu R\rho=\frac{-(\delta\phi^r_\delta+\delta^2\phi^r_{\delta\delta}+\delta\tau\phi^r_{\delta\tau})}{(1+\delta\phi^r_\delta-\delta\tau\phi^r_{\delta\tau})^2-\tau^2(\phi^\circ_{\tau\tau}+\phi^r_{\tau\tau})(1+2\delta\phi^r_\delta+\delta^2\phi^r_{\delta\delta})}$
Isothermal throttling coefficient $\delta_T=(\partial h/\partial p)_T$	$\delta_T\rho=1-\frac{1+\delta\phi^r_\delta-\delta\tau\phi^r_{\delta\tau}}{1+2\delta\phi^r_\delta+\delta^2\phi^r_{\delta\delta}}$
Isentropic temperature-pressure coefficient $\beta_s=(\partial T/\partial p)_s$	$\beta_s\rho R=\frac{1+\delta\phi^r_\delta-\delta\tau\phi^r_{\delta\tau}}{(1+\delta\phi^r_\delta-\delta\tau\phi^r_{\delta\tau})^2-\tau^2(\phi^\circ_{\tau\tau}+\phi^r_{\tau\tau})(1+2\delta\phi^r_\delta+\delta^2\phi^r_{\delta\delta})}$
Second virial coefficient $B(T)=\lim_{\rho\to0}(\partial(p/(\rho RT))/\partial\rho)_T$	$B(\tau)\rho_c=\lim_{\delta\to0}\phi^r_\delta(\delta,\tau)$
Third virial coefficient $C(T)=\lim_{\rho\to0}\left[\frac{1}{2}(\partial^2(p/(\rho RT))/\partial\rho^2)_T\right]$	$C(\tau)\rho_c^2=\lim_{\delta\to0}\phi^r_{\delta\delta}(\delta,\tau)$

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[a] $\phi^r_\delta=\left[\frac{\partial\phi^r}{\partial\delta}\right]_\tau,\quad \phi^r_{\delta\delta}=\left[\frac{\partial^2\phi^r}{\partial\delta^2}\right]_\tau,\quad \phi^r_\tau=\left[\frac{\partial\phi^r}{\partial\tau}\right]_\delta,\quad \phi^r_{\tau\tau}=\left[\frac{\partial^2\phi^r}{\partial\tau^2}\right]_\delta,\quad \phi^r_{\delta\tau}=\left[\frac{\partial^2\phi^r}{\partial\delta\partial\tau}\right],\quad \phi^\circ_\tau=\left[\frac{\partial\phi^\circ}{\partial\tau}\right]_\delta,\quad \phi^\circ_{\tau\tau}=\left[\frac{\partial^2\phi^\circ}{\partial\tau^2}\right]_\delta.$

[b] $\frac{\mathrm{d}p_\sigma}{\mathrm{d}T}=\frac{\rho''\cdot\rho'}{\rho''-\rho'}R\left[\ln\left(\frac{\rho''}{\rho'}\right)+\phi^r(\tau,\delta'')-\phi^r(\tau,\delta')-\tau(\phi^r_\tau(\tau,\delta'')-\phi^r_\tau(\tau,\delta'))\right].$

Razvoj formulacije

- del za idealni plin:

$$f^\circ(\rho,T)=h^\circ(T)-RT-Ts^\circ(\rho,T)$$

- $h = h(T)$, $s = s(T, \rho)$ =>

$$f^\circ(\rho,T)=\left(\int_{T_0}^{T} c_p^\circ \mathrm{d}T+h_0^\circ\right)-RT$$
$$-T\left[\int_{T_0}^{T}\frac{c_p^\circ-R}{T}\,\mathrm{d}T-R\ln\left(\frac{\rho}{\rho_0^\circ}\right)+s_0^\circ\right]$$

- c_p nam pove Planck-Einsteinova funkcija z eksperimentalno določenimi koeficienti:

$$\frac{c_p^\circ}{R}=1+n_3^\circ+\sum_{i=4}^{8} n_i^\circ\,\frac{(\gamma_i^\circ\tau)^2 e^{-\gamma_i^\circ\tau}}{[1-e^{-\gamma_i^\circ\tau}]^2}$$

Razvoj formulacije

- residualni del: minimiziramo funkcijo

$$\chi^2=\sum_{j=1}^{J}\chi_j^2=\sum_{j=1}^{J}\sum_{m=1}^{M_j}[[z_{\mathrm{exp}}-z_{\mathrm{calc}}(x_{\mathrm{exp}},y_{\mathrm{exp}},\overline{n})]^2]_{j,m}\cdot\sigma_{\mathrm{tot},m}$$

J različnih količin z_j (npr. pritisk, hitrost zvoka, …); M_j število eksperimentalnih vrednosti, uporabljenih za j-to količino.; *x* in *y* neodvisni spremenljivki, ki opredeljujeta vsako meritev – po navadi temperatura in tlak ali gostota

- obtežitev: $\sigma_{\mathrm{tot}}^2=\sigma_{\mathrm{exp}}^2/f_{\mathrm{wt}}^2$; $\sigma_{\mathrm{exp}}^2=\left[\frac{\partial\Delta z}{\partial x}\right]_{y,z}^2\sigma_x^2+\left[\frac{\partial\Delta z}{\partial y}\right]_{x,z}^2\sigma_y^2+\left[\frac{\partial\Delta z}{\partial z}\right]_{x,y}^2\sigma_z^2$

TABLE 5.1. Contribution of the several linear, nonlinear, and linearized data to the weighted sum of squares for the fitting and optimization

j	Type of data	Weighted sum of squares
		Linear data
1	$p(\rho,T)$	$\chi_1^2=\sum_{m=1}^{M}\left[\frac{p-\rho RT}{\rho^2 RT}-\rho_c^{-1}\phi_\delta^r\right]_m^2\cdot\sigma_m^{-2}$
2	$c_v(\rho,T)$	$\chi_2^2=\sum_{m=1}^{M}\left[\frac{c_v}{R}+\tau^2(\phi_{\tau\tau}^\circ+\phi_{\tau\tau}^r)\right]_m^2\cdot\sigma_m^{-2}$
3	$B(T)$	$\chi_3^2=\sum_{m=1}^{M}\left[B\cdot\rho_c-\lim_{\rho\to 0}\phi_\delta^r\right]_m^2\cdot\sigma_m^{-2}$
		Nonlinear data
4	$w(p,T)$	$\chi_4^2=\sum_{m=1}^{M}\left[\frac{w^2}{RT}-1-2\delta\phi_\delta^r-\delta^2\phi_{\delta\delta}^r+\frac{(1+\delta\phi_\delta^r-\delta\tau\phi_{\delta\tau}^r)^2}{\tau^2(\phi_{\tau\tau}^\circ+\phi_{\tau\tau}^r)}\right]_m^2\cdot\sigma_m^{-2}$
5	$c_p(p,T)$	$\chi_5^2=\sum_{m=1}^{M}\left[\frac{c_p}{R}+\tau^2(\phi_{\tau\tau}^\circ+\phi_{\tau\tau}^r)-\frac{(1+\delta\phi_\delta^r-\delta\tau\phi_{\delta\tau}^r)^2}{1+2\delta\phi_\delta^r+\delta^2\phi_{\delta\delta}^r}\right]_m^2\cdot\sigma_m^{-2}$
6	$h_2(p_2,T_2)-h_1(p_1,T_1)$	$\chi_6^2=\sum_{m=1}^{M}\left[\frac{h_2}{RT_2}-\frac{h_1}{RT_1}-[\tau(\phi_\tau^\circ-\phi_\tau^r)+\delta\phi_\delta^r]_2\right.$ $\left.+[\tau(\phi_\tau^\circ-\phi_\tau^r)+\delta\phi_\delta^r]_1\right]_m^2\cdot\sigma_m^{-2}$

7	$\mu(p,T)$	$\chi_7^2=\sum_{m=1}^{M}\left[\mu R\rho+\frac{(\delta\phi^{\mathrm{r}}_{\delta}+\delta^2\phi^{\mathrm{r}}_{\delta\delta}+\delta\tau\phi^{\mathrm{r}}_{\delta\tau})}{(1+\delta\phi^{\mathrm{r}}_{\delta}-\delta\tau\phi^{\mathrm{r}}_{\delta\tau})^2-\tau^2(\phi^{\circ}_{\tau\tau}+\phi^{\mathrm{r}}_{\tau\tau})(1+2\delta\phi^{\mathrm{r}}_{\delta}+\delta^2\phi^{\mathrm{r}}_{\delta\delta})}\right]_m^2\cdot\sigma_m^{-2}$
8	$\delta_T(p,T)$	$\chi_8^2=\sum_{m=1}^{M}\left[\delta_T\rho-1+\frac{1+\delta\phi^{\mathrm{r}}_{\delta}-\delta\tau\phi^{\mathrm{r}}_{\delta\tau}}{1+2\delta\phi^{\mathrm{r}}_{\delta}+\delta^2\phi^{\mathrm{r}}_{\delta\delta}}\right]_m^2\cdot\sigma_m^{-2}$
9	$p_\sigma(T)$	$\chi_9^2=\sum_{m=1}^{M}\left[\frac{p_{\sigma,m}-p_\sigma}{RT_{\mathrm{c}}\rho_{\mathrm{c}}}\right]_m^2\cdot\sigma_m^{-2}$
10	$\rho'(T)$	$\chi_{10}^2=\sum_{m=1}^{M}\left[\frac{\rho'_m-\rho'}{\rho_{\mathrm{c}}}\right]_m^2\cdot\sigma_m^{-2}$
11	$\rho''(T)$	$\chi_{11}^2=\sum_{m=1}^{M}\left[\frac{\rho''_m-\rho''}{\rho_{\mathrm{c}}}\right]_m^2\cdot\sigma_m^{-2}$
12	$u'_2(T_2)-u'_1(T_1)$	$\chi_{12}^2=\sum_{m=1}^{M}\left[\frac{u'_2}{RT_2}-\frac{u'_1}{RT_1}-[\tau(\phi^{\circ}_{\tau}+\phi^{\mathrm{r}}_{\tau})]_2+[\tau(\phi^{\circ}_{\tau}+\phi^{\mathrm{r}}_{\tau})]_1\right]_m^2\cdot\sigma_m^{-2}$
13	$u''(T)-u'(T)$	$\chi_{13}^2=\sum_{m=1}^{M}\left[\frac{u''-u'}{RT}-\tau\left[\ln\frac{\delta''}{\delta'}+\phi^{\mathrm{r}}_{\tau}(\delta'',\tau)-\phi^{\mathrm{r}}_{\tau}(\delta',\tau)\right]\right]_m^2\cdot\sigma_m^{-2}$
		Linearized data
4*	$w(\rho^{\mathrm{p}},T)$	$\chi_{4*}^2=\sum_{m=1}^{M}\left[\frac{w^2}{RT}-\gamma^{\mathrm{p}}\cdot(1+2\delta\phi^{\mathrm{r}}_{\delta}+\delta^2\phi^{\mathrm{r}}_{\delta\delta})\right]_m^2\cdot\sigma_m^{-2}$
5*	$c_p(\rho^{\mathrm{p}},T)$	$\chi_{5*}^2=\sum_{m=1}^{M}\left[\frac{c_p}{R}+\tau^2(\phi^{\circ}_{\tau\tau}+\phi^{\mathrm{r}}_{\tau\tau})-\epsilon^{\mathrm{p}}\right]_m^2\cdot\sigma_m^{-2}$
6*	$h_2(\rho^{\mathrm{p}}_2,T_2)-h_1(\rho^{\mathrm{p}}_1,T_1)$	$\chi_{6*}^2=\sum_{m=1}^{M}\left[\frac{h_2}{RT_2}-\frac{h_1}{RT_1}-[\tau(\phi^{\circ}_{\tau}-\phi^{\mathrm{r}}_{\tau})+\delta\phi^{\mathrm{r}}_{\delta}]_2+[\tau(\phi^{\circ}_{\tau}-\phi^{\mathrm{r}}_{\tau})+\delta\phi^{\mathrm{r}}_{\delta}]_1\right]_m^2\cdot\sigma_m^{-2}$

12*	$u_2'(\rho_2'^{\mathrm{p}},T_2)-u_1'(\rho_1'^{\mathrm{p}},T_1)$	$\chi^2_{12*}=\sum_{m=1}^{M}\left[\frac{u_2'}{RT_2}-\frac{u_1'}{RT_1}-[\tau(\phi^\circ_\tau+\phi^{\mathrm{r}}_\tau)]_2+[\tau(\phi^\circ_\tau+\phi^{\mathrm{r}}_\tau)]_1\right]^2_m\cdot\sigma_m^{-2}$
13*	$u''(\rho''^{\mathrm{p}},T)-u'(\rho'^{\mathrm{p}},T)$	$\chi^2_{13*}=\sum_{m=1}^{M}\left[\frac{u''-u'}{RT}-\tau\left[\ln\frac{\delta''}{\delta'}+\phi^{\mathrm{r}}_\tau(\delta'',\tau)-\phi^{\mathrm{r}}_\tau(\delta',\tau)\right]\right]^2_m\cdot\sigma_m^{-2}$
14	$p(\rho'^{\mathrm{p}},T)$	$\chi^2_{14}=\sum_{m=1}^{M}\left[\frac{p_\sigma-\rho'RT}{(\rho')^2RT}-\rho_{\mathrm{c}}^{-1}\phi^{\mathrm{r}}_\delta(\delta',\tau)\right]^2_m\cdot\sigma_m^{-2}$
15	$p(\rho''^{\mathrm{p}},T)$	$\chi^2_{15}=\sum_{m=1}^{M}\left[\frac{p_\sigma-\rho''RT}{(\rho'')^2RT}-\rho_{\mathrm{c}}^{-1}\phi^{\mathrm{r}}_\delta(\delta'',\tau)\right]^2_m\cdot\sigma_m^{-2}$
16	Maxwell criterion	$\chi^2_{16}=\sum_{m=1}^{M}\left[\frac{p_\sigma}{RT}\cdot\left[\frac{1}{\rho''}-\frac{1}{\rho'}\right]-\ln\left[\frac{\rho'}{\rho''}\right]-[\phi^{\mathrm{r}}(\delta',\tau)-\phi^{\mathrm{r}}(\delta'',\tau)]\right]^2_m\cdot\sigma_m^{-2}$

Explanations

For the relations between the several properties and ϕ° and ϕ^{r} and their derivatives see Table 6.3.
For the weighted sum of squares the following abbreviations and definitions are used:

(1) $\phi^{\mathrm{r}}_\delta=\left[\frac{\partial\phi^{\mathrm{r}}}{\partial\delta}\right]_\tau,\ \phi^{\mathrm{r}}_{\delta\delta}=\left[\frac{\partial^2\phi^{\mathrm{r}}}{\partial\delta^2}\right]_\tau,\ \phi^{\mathrm{r}}_\tau=\left[\frac{\partial\phi^{\mathrm{r}}}{\partial\tau}\right]_\delta,\ \phi^{\mathrm{r}}_{\tau\tau}=\left[\frac{\partial^2\phi^{\mathrm{r}}}{\partial\tau^2}\right]_\delta,\ \phi^{\mathrm{r}}_{\delta\tau}=\left[\frac{\partial^2\phi^{\mathrm{r}}}{\partial\delta\partial\tau}\right],\ \phi^\circ_\tau=\left[\frac{\partial\phi^\circ}{\partial\tau}\right]_\delta,\ \phi^\circ_{\tau\tau}=\left[\frac{\partial^2\phi^\circ}{\partial\tau^2}\right]_\delta.$

(2) The weight σ_m corresponds to the quantity σ_{tot} according to Eq. (5.9).
(3) The subscript p means precorrelated. The precorrelation factors γ^{p} and ϵ^{p} are defined by the relations:

$$\gamma^{\mathrm{p}}=\frac{c_p(\rho^{\mathrm{p}},T)}{c_v(\rho^{\mathrm{p}},T)}$$

$$\epsilon^{\mathrm{p}}=c_p-c_v=\left[\frac{(1+\delta\phi^{\mathrm{r}}_\delta-\delta\tau\phi^{\mathrm{r}}_{\delta\tau})^2}{1+2\delta\phi^{\mathrm{r}}_\delta+\delta^2\phi^{\mathrm{r}}_{\delta\delta}}\right]_{\tau,\delta^{\mathrm{p}}}$$

All precorrelated quantities are calculated from a preliminary equation of state.

Razvoj formulacije

- nimamo podatkov o strukturi residualnega dela
- banka členov
- s statistično-stohastičnimi metodami izberemo ustrezno kombinacijo
- optimizacija je rekurzivna – potrebujemo enačbo stanja (oz. ustrezen približek)

Razvoj formulacije

- banka členov, odvisnih od reducirane gostote in inverzne reducirane temperature
- členi 4 tipov:
- polinomi $\phi_i^{\mathrm{r}} = n_i \delta^{d_i} \tau^{t_i}$
- polinomi in eksponenti $\phi_i^{\mathrm{r}} = n_i \delta^{d_i} \tau^{t_i} e^{-\delta^{c_i}}.$
- podobni Gaussu $\phi_i^{\mathrm{r}} = n_i \delta^{d_i} \tau^{t_i} e^{-\alpha_i(\delta-\epsilon_i)^2 - \beta_i(\tau-\gamma_i)^2}$
- neanalitični

$$\phi_i^{\mathrm{r}} = n_i \Delta^{b_i} \delta \psi,$$

$$\Delta = \theta^2 + B_i[(\delta - 1)^2]^{a_i},$$

$$\theta = (1 - \tau) + A_i[(\delta - 1)^2]^{1/(2\beta_i)},$$

$$\psi = e^{-C_i(\delta-1)^2 - D_i(\tau-1)^2}.$$

Razvoj formulacije

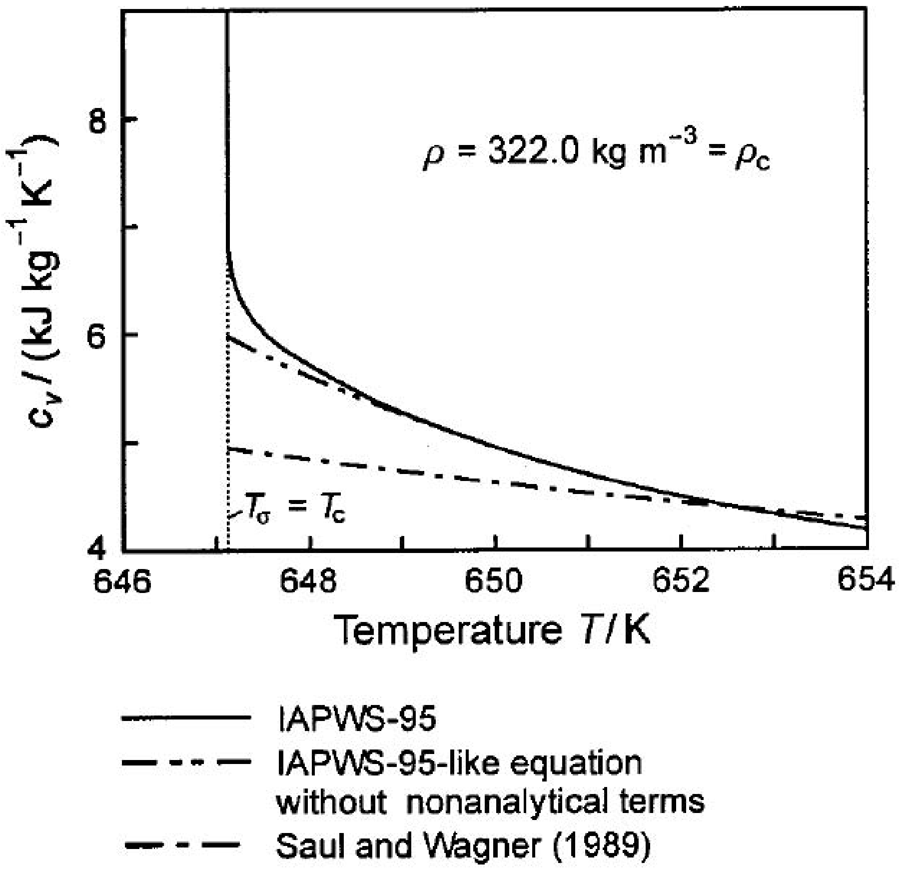
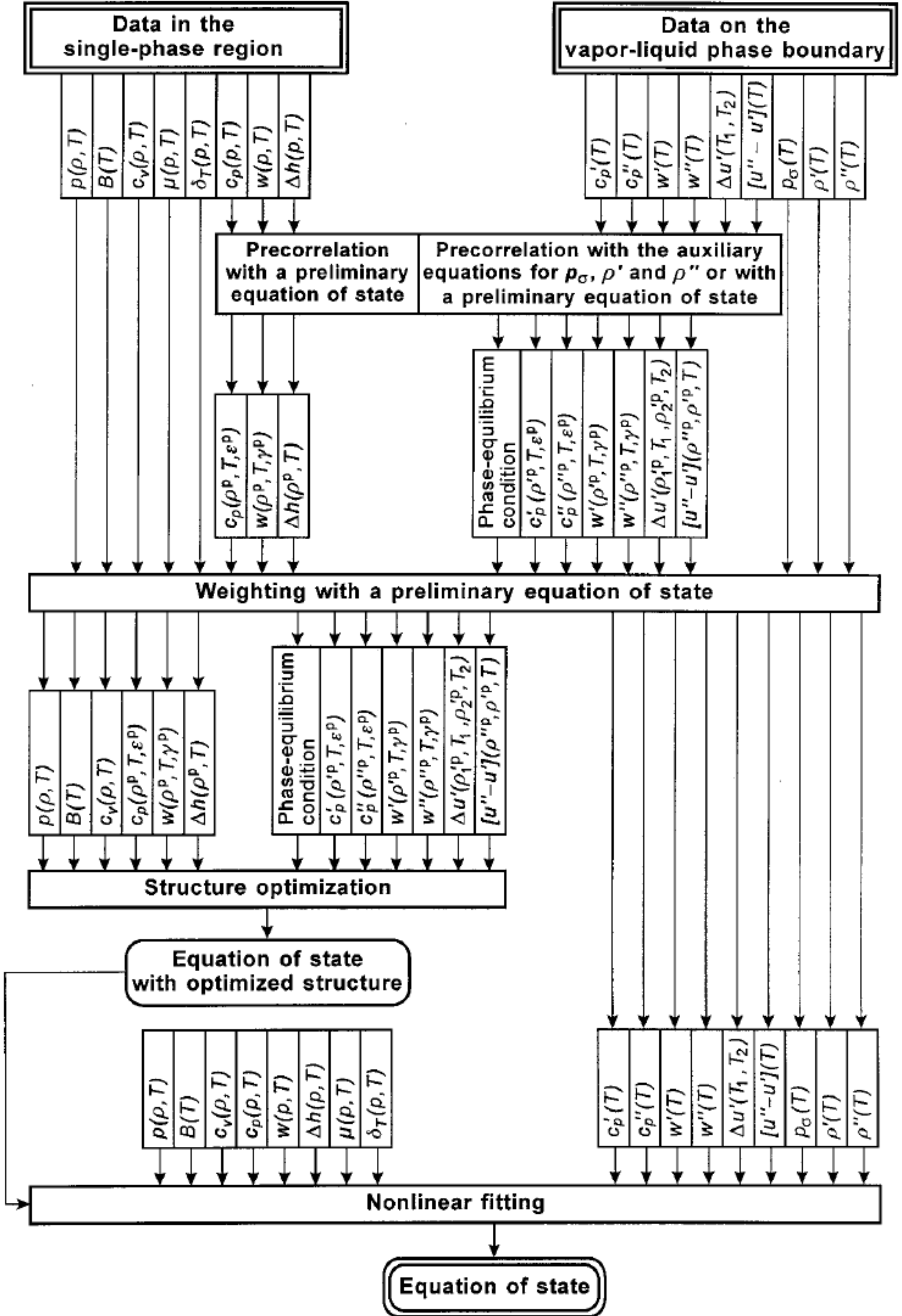


FIG. 6.5. Isochoric heat capacity in the critical region as a function of temperature (on the critical isochore of the single-phase region) calculated from IAPWS-95, Eq. (6.4), an IAPWS-95-like equation but without nonanalytical terms, and the equation of Saul and Wagner (1989).

Razvoj formulacije

- izbranih 745 členov => splošna oblika za kapljevinski del enačbe stanja:

$$
\begin{aligned}
\phi^{\mathrm{r}} = {} & \sum_{i=1}^{5}\sum_{j=-4}^{8} n_{ij}\delta^{i}\tau^{j/8} + e^{-\delta}\sum_{i=1}^{15}\sum_{j=1}^{16} n_{ij}\delta^{i}\tau^{j} \\
& + e^{-\delta^{2}}\sum_{i=1}^{12}\sum_{j=1}^{10} n_{ij}\delta^{i}\tau^{j} + e^{-\delta^{3}}\sum_{i=1}^{5}\sum_{j=10}^{23} n_{ij}\delta^{i}\tau^{j} \\
& + e^{-\delta^{4}}\sum_{i=1}^{9}\sum_{j=10}^{20} n_{ij}\delta^{2i}\tau^{j} + e^{-\delta^{6}}\sum_{i=3}^{7}\sum_{j=12}^{25} n_{ij}\delta^{i}\tau^{2j} \\
& + \sum_{i=1}^{45} n_{i}\delta^{d_i}\tau^{t_i}e^{-\alpha_i(\delta-\epsilon_i)^2-\beta_i(\tau-\gamma_i)^2} \\
& + \sum_{i=1}^{1}\sum_{j=1}^{4}\sum_{k=1}^{3}\sum_{l=1}^{1}\sum_{m=1}^{3} n_{ijklm}\Delta^{b_j}\delta\psi,
\end{aligned}
$$


Data in the single-phase region
$p(\rho,T)$
$B(T)$
$c_v(\rho,T)$
$\mu(p,T)$
$\delta_T(p,T)$
$c_p(p,T)$
$w(p,T)$
$\Delta h(p,T)$
Data on the vapor-liquid phase boundary
$c_p'(T)$
$c_p''(T)$
$w'(T)$
$w''(T)$
$\Delta u'(T_1,T_2)$
$[u''-u'](T)$
$p_\sigma(T)$
$\rho'(T)$
$\rho''(T)$
Precorrelation with a preliminary equation of state
Precorrelation with the auxiliary equations for p_σ, ρ' and ρ'' or with a preliminary equation of state
$c_p(\rho^p,T,\varepsilon^p)$
$w(\rho^p,T,\gamma^p)$
$\Delta h(\rho^p,T)$
Phase-equilibrium condition
$c_p'(\rho'^p,T,\varepsilon^p)$
$c_p''(\rho''^p,T,\varepsilon^p)$
$w'(\rho'^p,T,\gamma^p)$
$w''(\rho''^p,T,\gamma^p)$
$\Delta u'(\rho_1'^p,T_1,\rho_2'^p,T_2)$
$[u''-u'](\rho''^p,\rho'^p,T)$
Weighting with a preliminary equation of state
$p(\rho,T)$
$B(T)$
$c_v(\rho,T)$
$c_p(\rho^p,T,\varepsilon^p)$
$w(\rho^p,T,\gamma^p)$
$\Delta h(\rho^p,T)$
Phase-equilibrium condition
$c_p'(\rho'^p,T,\varepsilon^p)$
$c_p''(\rho''^p,T,\varepsilon^p)$
$w'(\rho'^p,T,\gamma^p)$
$w''(\rho''^p,T,\gamma^p)$
$\Delta u'(\rho_1'^p,T_1,\rho_2'^p,T_2)$
$[u''-u'](\rho''^p,\rho'^p,T)$
Structure optimization
Equation of state with optimized structure
$p(\rho,T)$
$B(T)$
$c_v(\rho,T)$
$c_p(p,T)$
$w(p,T)$
$\Delta h(p,T)$
$\mu(p,T)$
$\delta_T(p,T)$
$c_p'(T)$
$c_p''(T)$
$w'(T)$
$w''(T)$
$\Delta u'(T_1,T_2)$
$[u''-u'](T)$
$p_\sigma(T)$
$\rho'(T)$
$\rho''(T)$
Nonlinear fitting
Equation of state

Razvoj formulacije

- enačba stanja vode in vodne pare:

$$\frac{f(\rho,T)}{RT}=\phi(\delta,\tau)=\phi^{\circ}(\delta,\tau)+\phi^{\mathrm{r}}(\delta,\tau),$$

where $\delta=\rho/\rho_c$ and $\tau=T_c/T$

$$\phi^{\circ}=\ln\delta+n_1^{\circ}+n_2^{\circ}\tau+n_3^{\circ}\ln\tau+\sum_{i=4}^{8}n_i^{\circ}\ln[1-e^{-\gamma_i^{\circ}\tau}]$$

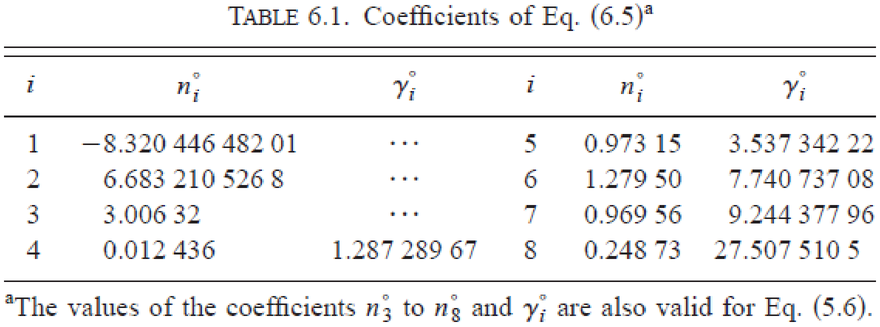


TABLE 6.1. Coefficients of Eq. (6.5)[a]

i	n_i°	γ_i°	i	n_i°	γ_i°
1	−8.320 446 482 01	⋯	5	0.973 15	3.537 342 22
2	6.683 210 526 8	⋯	6	1.279 50	7.740 737 08
3	3.006 32	⋯	7	0.969 56	9.244 377 96
4	0.012 436	1.287 289 67	8	0.248 73	27.507 510 5

[a] The values of the coefficients n_3° to n_8° and γ_i° are also valid for Eq. (5.6).

$$\phi^{\mathrm{r}}=\sum_{i=1}^{7}n_i\delta^{d_i}\tau^{t_i}+\sum_{i=8}^{51}n_i\delta^{d_i}\tau^{t_i}e^{-\delta^{c_i}}$$

$$+\sum_{i=52}^{54}n_i\delta^{d_i}\tau^{t_i}e^{-\alpha_i(\delta-\epsilon_i)^2-\beta_i(\tau-\gamma_i)^2}+\sum_{i=55}^{56}n_i\Delta^{b_i}\delta\psi$$

i	c_i	d_i	t_i	n_i
1	⋯	1	−0.5	$0.125\,335\,479\,355\,23\times10^{-1}$
2	⋯	1	0.875	$0.789\,576\,347\,228\,28\times10^{1}$
3	⋯	1	1	$-0.878\,032\,033\,035\,61\times10^{1}$
4	⋯	2	0.5	$0.318\,025\,093\,454\,18$
5	⋯	2	0.75	$-0.261\,455\,338\,593\,58$
6	⋯	3	0.375	$-0.781\,997\,516\,879\,81\times10^{-2}$
7	⋯	4	1	$0.880\,894\,931\,021\,34\times10^{-2}$
8	1	1	4	$-0.668\,565\,723\,079\,65$
9	1	1	6	$0.204\,338\,109\,509\,65$
10	1	1	12	$-0.662\,126\,050\,396\,87\times10^{-4}$
11	1	2	1	$-0.192\,327\,211\,560\,02$
12	1	2	5	$-0.257\,090\,430\,034\,38$
13	1	3	4	$0.160\,748\,684\,862\,51$
14	1	4	2	$-0.400\,928\,289\,258\,07\times10^{-1}$
15	1	4	13	$0.393\,434\,226\,032\,54\times10^{-6}$
16	1	5	9	$-0.759\,413\,770\,881\,44\times10^{-5}$
17	1	7	3	$0.562\,509\,793\,518\,88\times10^{-3}$
18	1	9	4	$-0.156\,086\,522\,571\,35\times10^{-4}$
19	1	10	11	$0.115\,379\,964\,229\,51\times10^{-8}$
20	1	11	4	$0.365\,821\,651\,442\,04\times10^{-6}$
21	1	13	13	$-0.132\,511\,800\,746\,68\times10^{-11}$
22	1	15	1	$-0.626\,395\,869\,124\,54\times10^{-9}$
23	2	1	7	$-0.107\,936\,009\,089\,32$
24	2	2	1	$0.176\,114\,910\,087\,52\times10^{-1}$
25	2	2	9	$0.221\,322\,951\,675\,46$
26	2	2	10	$-0.402\,476\,697\,635\,28$
27	2	3	10	$0.580\,833\,999\,857\,59$
28	2	4	3	$0.499\,691\,469\,908\,06\times10^{-2}$
29	2	4	7	$-0.313\,587\,007\,125\,49\times10^{-1}$
30	2	4	10	$-0.743\,159\,297\,103\,41$
31	2	5	10	$0.478\,073\,299\,154\,80$
32	2	6	6	$0.205\,279\,408\,959\,48\times10^{-1}$
33	2	6	10	$-0.136\,364\,351\,103\,43$
34	2	7	10	$0.141\,806\,344\,006\,17\times10^{-1}$
35	2	9	1	$0.833\,265\,048\,807\,13\times10^{-2}$
36	2	9	2	$-0.290\,523\,360\,095\,85\times10^{-1}$
37	2	9	3	$0.386\,150\,855\,742\,06\times10^{-1}$
38	2	9	4	$-0.203\,934\,865\,137\,04\times10^{-1}$
39	2	9	8	$-0.165\,540\,500\,637\,34\times10^{-2}$
40	2	10	6	$0.199\,555\,719\,795\,41\times10^{-2}$
41	2	10	9	$0.158\,703\,083\,241\,57\times10^{-3}$
42	2	12	8	$-0.163\,885\,683\,425\,30\times10^{-4}$
43	3	3	16	$0.436\,136\,157\,238\,11\times10^{-1}$
44	3	4	22	$0.349\,940\,054\,637\,65\times10^{-1}$
45	3	4	23	$-0.767\,881\,978\,446\,21\times10^{-1}$
46	3	5	23	$0.224\,462\,773\,320\,06\times10^{-1}$
47	4	14	10	$-0.626\,897\,104\,146\,85\times10^{-4}$
48	6	3	50	$-0.557\,111\,185\,656\,45\times10^{-9}$
49	6	6	44	$-0.199\,057\,183\,544\,08$
50	6	6	46	$0.317\,774\,973\,307\,38$
51	6	6	50	$-0.118\,411\,824\,259\,81$

i	c_i	d_i	t_i	n_i	α_i	β_i	γ_i	ϵ_i
52	⋯	3	0	$-0.313\,062\,603\,234\,35\times10^{2}$	20	150	1.21	1
53	⋯	3	1	$0.315\,461\,402\,377\,81\times10^{2}$	20	150	1.21	1
54	⋯	3	4	$-0.252\,131\,543\,416\,95\times10^{4}$	20	250	1.25	1

i	a_i	b_i	B_i	n_i	C_i	D_i	A_i	β_i
55	3.5	0.85	0.2	$-0.148\,746\,408\,567\,24$	28	700	0.32	0.3
56	3.5	0.95	0.2	$0.318\,061\,108\,784\,44$	32	800	0.32	0.3

Veljavnost

- velja za celotno območje od tališča ledu (najnižja temperatura 251,156 K pri 209,9 MPa) do 1273 K in pritiska do 1000 MPa
- v območju stabilne kapljevine se da ekstrapolirati do 100 GPa in do 5000 K (vsaj za gostoto in entalpijo)
- ustrezno se ekstrapolira tudi v območje podhlajene in pregrete tekočine, ne pa podhlajene pare

Napake

- odvisne od količine

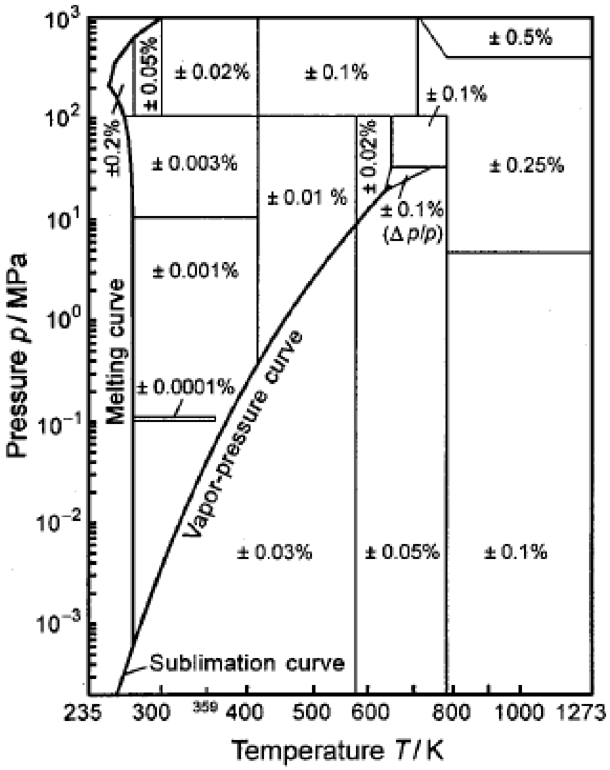


FIG. 6.1. Percentage uncertainties in density estimated for IAPWS-95, Eq. (6.4). In the enlarged critical region (triangle), the uncertainty is given as percentage uncertainty in pressure. This region is bordered by the two isochores 527 and 144 kg m^{-3} and by the 30 MPa isobar. The positions of the lines separating the uncertainty regions are approximate.

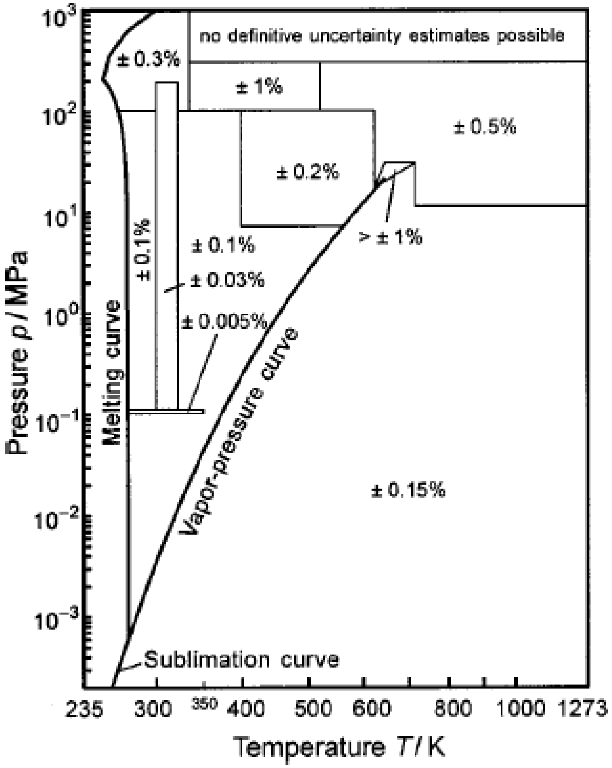


FIG. 6.2. Percentage of uncertainties in speed of sound estimated for IAPWS-95, Eq. (6.4). For the uncertainty in the triangle around the critical point, see the text; for the definition of this region, see Fig. 6.1. The positions of the lines separating the uncertainty regions are approximate.

Napake

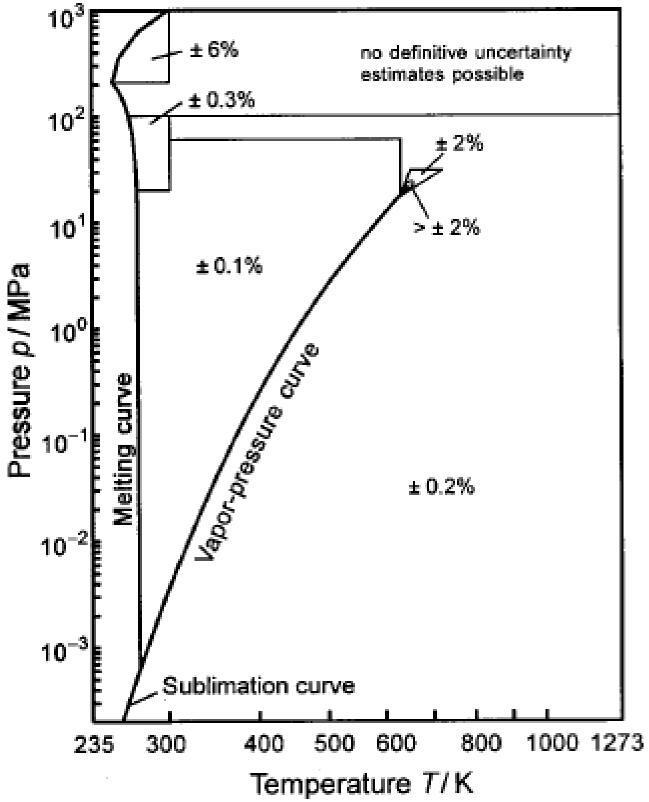


FIG. 6.3. Percentage uncertainties in specific isobaric heat capacity estimated for IAPWS-95, Eq. (6.4). For the uncertainty in the immediate vicinity of the critical point, see the text; for the definition of the triangle around the critical point, see Fig. 6.1. The positions of the lines separating the uncertainty regions are approximate.

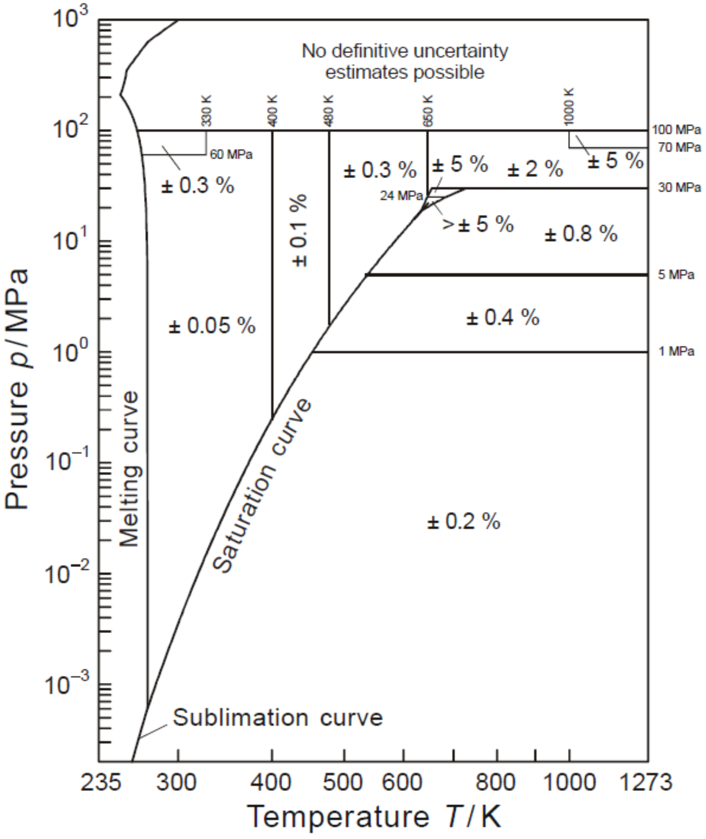


Figure 3 Percentage uncertainties $\Delta(\Delta h)/\Delta h$ in *adiabatic* enthalpy differences Δh estimated for IAPWS-95. The uncertainty values given relate to enthalpy differences along adiabatic reversible (isentropic) and adiabatic irreversible paths (steam turbines, boiler feed pumps, and hydroturbines). In the gas region, the uncertainty values correspond to enthalpy differences of $10 \le \Delta h/(\mathrm{kJ\,kg^{-1}}) \le 1000$, whereas in the liquid region, the uncertainty values correspond to enthalpy differences of $1 \le \Delta h/(\mathrm{kJ\,kg^{-1}}) \le 10$. The positions of the lines separating the uncertainty regions, marked by the given values of temperature and pressure, are approximate. For the definition of the enlarged critical region, see Fig. 1.

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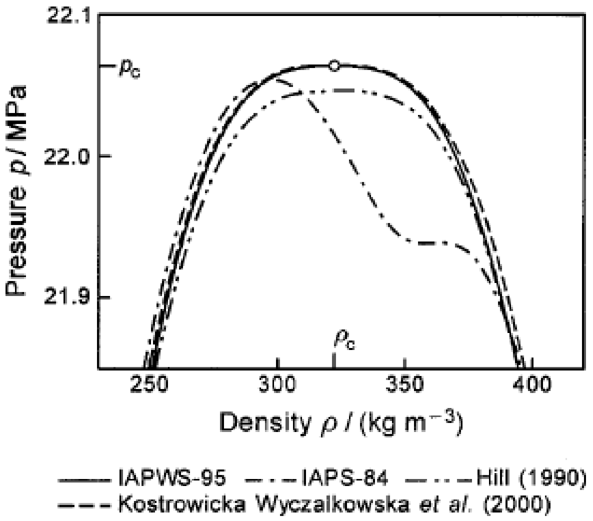

FIG. 7.4. The vapor–liquid phase boundary in the critical region of the $p-\rho$ diagram calculated from IAPWS-95, Eq. (6.4), IAPS-84, the equation of Hill (1990), and the crossover equation of Kostrowicka Wyczalkowska *et al.* (2000).

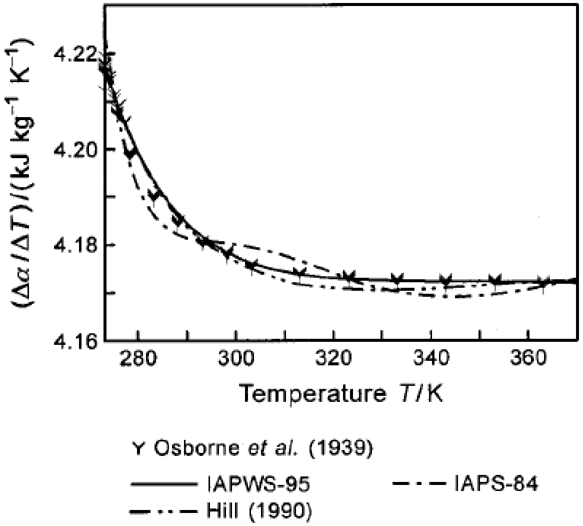

FIG. 7.8. The caloric difference quantity $\Delta\alpha$ related to ΔT (with $\Delta T = 1$ K) as a function of temperature calculated from IAPWS-95, Eq. (6.4), IAPS-84, and the equation of Hill (1990). The experimental data $\Delta\alpha/\Delta T$ of Osborne *et al.* (1939) are plotted for comparison.

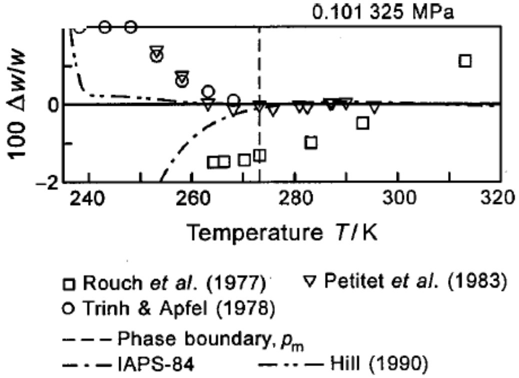

FIG. 7.50. Percentage deviations $100\Delta w/w = 100(w_{\text{exp}} - w_{\text{calc}})/w_{\text{exp}}$ between experimental data of the speed of sound w in the subcooled liquid along the isobar $p = 0.101\ 325$ MPa and values calculated from IAPWS-95, Eq. (6.4). Values calculated from IAPS-84 and the equation of Hill (1990) are plotted for comparison.

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- http://webbook.nist.gov/chemistry/fluid/

- če ni drugače označeno, so vse slike iz članka Wagnerja in Prußa