Thermodynamic Properties for *Real* Moist Air, Dry Air, Steam, Water, and Ice (ASHRAE RP-1485)

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Outline

- Background
- ASHRAE Research Project RP-1485
- Underlying Properties
  - Dry Air
  - Steam, Water, and Ice
- Psychrometric Equations
- Results
- Conclusions

Background

Prior ASHRAE Real Moist Air Psychrometric Research

- Goff and Gratch Research (1943-1949):
  - Originated the enhancement factor, provided equations for its calculation
  - Basis for ASHRAE charts and tables up to 1981

- Hyland and Wexler Research (1978-1983):
  - Complete update of the former model
  - Including new slightly modified physical constants
  - Ice formulation used worldwide up to 2006
  - Update the ASHRAE Handbook moist air tables

- Nelson and Sauer Research (1999-2001):
  - Extension in temperature up to 320°C
  - Updates only above 0°C, change to ITS-90 temperature scale

Background

Projects at the Zittau/Görlitz University of Applied Sciences regarding Moist Air and Steam and Water

- “Advanced Adiabatic Compressed Air Energy Storage” (AA-CAES) Project of the European Union (2003-2006)
  - PTB Report “Determination of Thermodynamic and Transport Properties of Humid Air for Power Cycle Calculations”
  - Paper in ASME Journal of Engineering for Gas Turbines and Power (April 2010)
- “Industrial Formulation IAPWS-IF97” and “Supplementary Releases on Backward Equations for IAPWS-IF97” Projects of the International Association for the Properties of Water and Steam IAPWS (1991-1997 and 2000-2005)
- Chairmanship of the IAPWS Working Group “Thermophysical Properties of Water and Steam (TPWS)” (since 2005)

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Nearly two decades’ experience in the field
“Properties of steam, water, and moist air”

ASHRAE Research Project RP-1485

Aims

- Update of the moist air and water saturation tables in the 2009 ASHRAE Handbook of Fundamentals
- Completely update the 1983 ASHRAE Hyland-Wexler model
- Extend the range of validity to:

  $-143.15°\text{C} \le t < 350°\text{C}$

  $0.01\,\text{kPa} \le p \le 10\,\text{MPa}$

  $0 \le W \le 10\,\text{kg}_\text{w}/\text{kg}_\text{a}$

Nelson-Sauer RP-1060 (July 2001):

$0°\text{C} \le t < 320°\text{C}$

$70\,\text{kPa} \le p \le 5\,\text{MPa}$

$0 \le W \le 1\,\text{kg}_\text{w}/\text{kg}_\text{a}$

Processing

- TC 1.1 approved ASHRAE Research Project 1485 (October 2007)
- RP-1485 was started in December 2007, ended in March 2009
- Technical Paper was published in the Journal HVAC&R Research in September 2009

Underlying Properties

Dry Air

- Molar mass of dry air from Gatley et al. (2008)
- NIST Reference Equation of Lemmon et al. (2000)
  - fundamental equation for the molar Helmholtz energy

$$\frac{\bar{a}(\rho,T)}{\bar{R}^{Lem}\,T} = \alpha(\delta,\tau) = \alpha^{\mathrm{o}}(\delta,\tau) + \alpha^{\mathrm{r}}(\delta,\tau)$$

ideal-gas part   residual part

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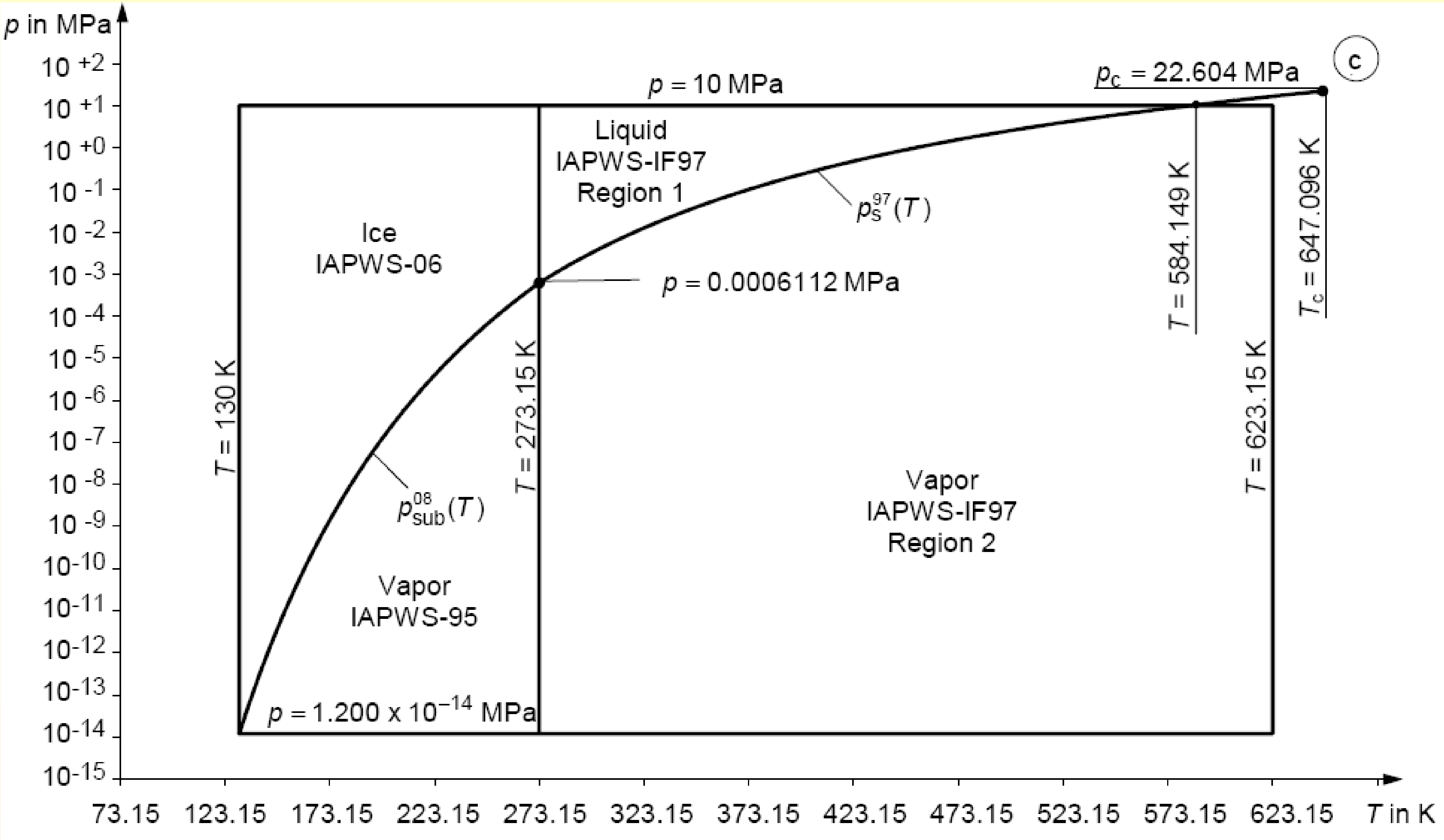
NIST Reference Equation leads to
high accuracy in the dry air part calculation of moist air

Underlying Properties

Steam, Water, and Ice



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Underlying Properties

Steam, Water, and Ice

- Applied IAPWS standards
  - "Revised Release on the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam" (IAPWS-IF97)
  - "Revised Release on the IAPWS Formulation 1995 for the Thermodynamic Properties of Ordinary Water Substance for General and Scientific Use" (IAPWS-95)
  - "Revised Release on an Equation of State 2006 for H_2O Ice Ih" (IAPWS-06)
  - "Revised Release 2008 on the Pressure along the Melting and Sublimation Curves of Ordinary Water Substance" (IAPWS-08)
- Molar mass of water from IAPWS-95

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IAPWS (International Association for the Properties of Water and Steam) H_2O models are the International Gold Standard for the properties of water and steam

Psychrometric Equations

Methodology

- Calculation of the second and third molar virial coefficients B_{aa} and C_{aaa} for dry air from the fundamental equation of Lemmon et al. (2000)
- Calculation of the second and third molar virial coefficients B_{ww} and C_{www} for water and steam from IAPWS-95
- Calculation of the air-water second molar cross-virial coefficient B_{aw} from Harvey and Huang (2007)
- Calculation of the air-water third molar cross-virial coefficients C_{aaw} and C_{aww} from Nelson and Sauer (2002)
- Calculation of the saturation pressure of water from IAPWS-IF97 and of the sublimation pressure from IAPWS-08
- Calculation of the isothermal compressibility of liquid water from IAPWS-IF97 and that of ice from IAPWS-06 in the enhancement factor equation
- Calculation of Henry's constant in the enhancement factor equation from the IAPWS Guideline 2004
- Value for the universal gas constant from Mohr and Taylor (2005)

Psychrometric Equations

- Virial Equation of State

$$\frac{p\overline{v}}{\overline{R}T} = 1 + \frac{B_\mathrm{m}}{\overline{v}} + \frac{C_\mathrm{m}}{\overline{v}^2}$$

  - Molar virial mixing coefficients

$$B_\mathrm{m} = \left(1-\psi_\mathrm{w}\right)^2 B_\mathrm{aa} + 2\left(1-\psi_\mathrm{w}\right)\psi_\mathrm{w} B_\mathrm{aw} + \psi_\mathrm{w}^2 B_\mathrm{ww}$$

$$C_\mathrm{m} = \left(1-\psi_\mathrm{w}\right)^3 C_\mathrm{aaa} + 3\left(1-\psi_\mathrm{w}\right)^2 \psi_\mathrm{w} C_\mathrm{aaw} + 3\left(1-\psi_\mathrm{w}\right)\psi_\mathrm{w}^2 C_\mathrm{aww} + \psi_\mathrm{w}^3 C_\mathrm{www}$$

- Enthalpy

$$\overline{h}(T,\overline{v},\psi_\mathrm{w}) = \overline{h}_0 + \left(1-\psi_\mathrm{w}\right)\overline{h}_\mathrm{a}^\mathrm{o} + \psi_\mathrm{w}\,\overline{h}_\mathrm{w}^\mathrm{o} + \overline{R}\,T\left[\left(B_\mathrm{m} - T\frac{\mathrm{d}B_\mathrm{m}}{\mathrm{d}T}\right)\frac{1}{\overline{v}} + \left(C_\mathrm{m} - \frac{T}{2}\frac{\mathrm{d}C_\mathrm{m}}{\mathrm{d}T}\right)\frac{1}{\overline{v}^2}\right]$$

- Entropy

$$\overline{s}(p,T,\psi_\mathrm{w}) = \overline{s}_0 + \left(1-\psi_\mathrm{w}\right)\overline{s}_\mathrm{a}^\mathrm{o} + \psi_\mathrm{w}\,\overline{s}_\mathrm{w}^\mathrm{o} - \overline{R}\left[\begin{array}{l}\left(B_\mathrm{m} + T\dfrac{\mathrm{d}B_\mathrm{m}}{\mathrm{d}T}\right)\dfrac{1}{\overline{v}} + \left(C_\mathrm{m} + T\dfrac{\mathrm{d}C_\mathrm{m}}{\mathrm{d}T}\right)\dfrac{1}{2\overline{v}^2} + \\ \left(1-\psi_\mathrm{w}\right)\ln\left(1-\psi_\mathrm{w}\right) + \psi_\mathrm{w}\ln\left(\psi_\mathrm{w}\right)\end{array}\right]$$

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Psychrometric Equations

- Enhancement factor equation

$$\begin{aligned}
\ln(f) = {} & (\bar{R}T)^{-1}\left[\left(1+\kappa_T\ p_{\mathrm{w,s}}\right)\left(p-p_{\mathrm{w,s}}\right)-0.5\,\kappa_T\left(p^2-p_{\mathrm{w,s}}^2\right)\right]\bar{v}_{\mathrm{w,s}}+\ln\left[1-\beta_{\mathrm{H}}\left(1-\psi_{\mathrm{w,s}}\right)p\right]+\\
& (\bar{R}T)^{-1}\left\{\left(1-\psi_{\mathrm{w,s}}\right)^2 p\,B_{\mathrm{aa}}-2\left(1-\psi_{\mathrm{w,s}}\right)^2 p\,B_{\mathrm{aw}}-\left[p-p_{\mathrm{w,s}}-\left(1-\psi_{\mathrm{w,s}}\right)^2\right]p\,B_{\mathrm{ww}}\right\}+\\
& (\bar{R}T)^{-2}\left\{\left(1-\psi_{\mathrm{w,s}}\right)^3 p^2\,C_{\mathrm{aaa}}+3\left[0.5-\left(1-\psi_{\mathrm{w,s}}\right)\right]\left(1-\psi_{\mathrm{w,s}}\right)^2 p^2\,C_{\mathrm{aaw}}-\right.\\
& 3\,\psi_{\mathrm{w,s}}\left(1-\psi_{\mathrm{w,s}}\right)^2 p^2\,C_{\mathrm{aww}}-0.5\left[\left(3-2\psi_{\mathrm{w,s}}\right)\psi_{\mathrm{w,s}}^2 p^2-p_{\mathrm{w,s}}^2\right]C_{\mathrm{www}}-\\
& \psi_{\mathrm{w,s}}\left(-2+3\psi_{\mathrm{w,s}}\right)\left(1-\psi_{\mathrm{w,s}}\right)^2 p^2\,B_{\mathrm{aa}}B_{\mathrm{ww}}-2\left(-1+3\psi_{\mathrm{w,s}}\right)\left(1-\psi_{\mathrm{w,s}}\right)^3 p^2\,B_{\mathrm{aa}}B_{\mathrm{aw}}+\\
& 6\,\psi_{\mathrm{w,s}}^2\left(1-\psi_{\mathrm{w,s}}\right)^2 p^2\,B_{\mathrm{aw}}B_{\mathrm{ww}}-1.5\left(1-\psi_{\mathrm{w,s}}\right)^4 p^2\,B_{\mathrm{aa}}^2-\\
& \left.2\,\psi_{\mathrm{w,s}}\left(-2+3\,\psi_{\mathrm{w,s}}\right)\left(1-\psi_{\mathrm{w,s}}\right)^2 p^2\,B_{\mathrm{aw}}^2-0.5\left[p_{\mathrm{w,s}}^2-\left(4-3\,\psi_{\mathrm{w,s}}\right)\psi_{\mathrm{w,s}}^3 p^2\right]B_{\mathrm{ww}}^2\right\}
\end{aligned}$$

- Equation for the saturation partial pressure of water

$$p_{\mathrm{s}} = f\ p_{\mathrm{w,s}}$$

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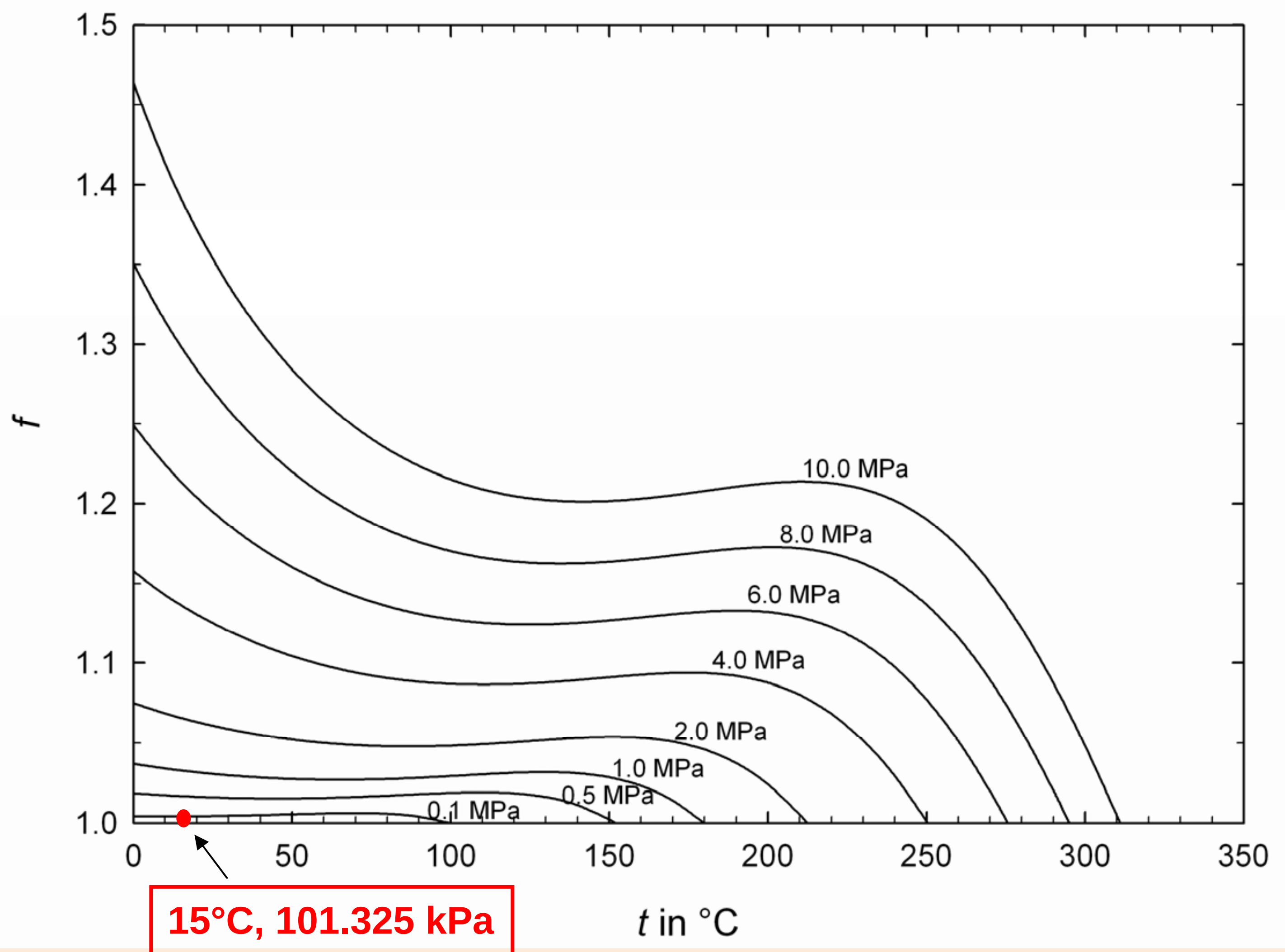
Psychrometric Equations

- Enhancement factor plotted over temperature



15°C, 101.325 kPa
***f* = 1.004**

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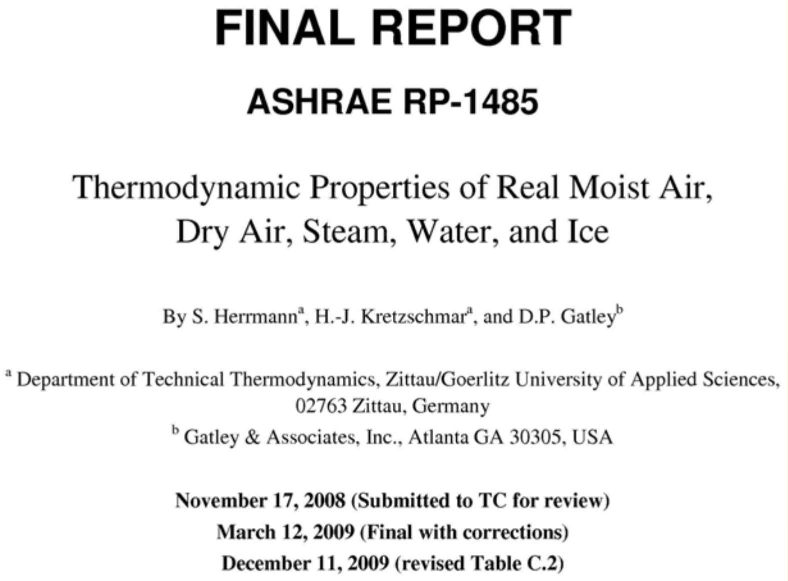
Results

Final Report of ASHRAE RP-1485



FINAL REPORT

ASHRAE RP-1485

Thermodynamic Properties of Real Moist Air,
Dry Air, Steam, Water, and Ice

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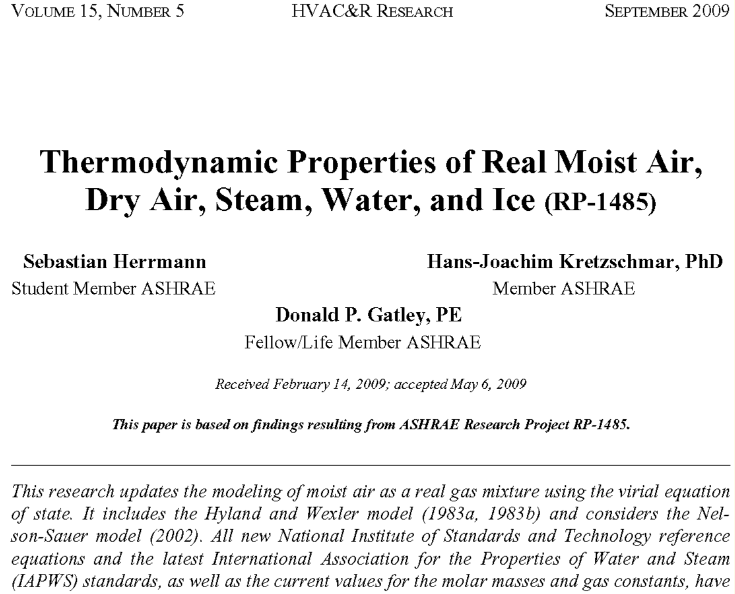
March 12, 2009 (Final with corrections)
December 11, 2009 (revised Table C.2)

Paper in ASHRAE Journal *HVAC&R Research*



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Thermodynamic Properties of Real Moist Air, Dry Air, Steam, Water, and Ice (RP-1485)

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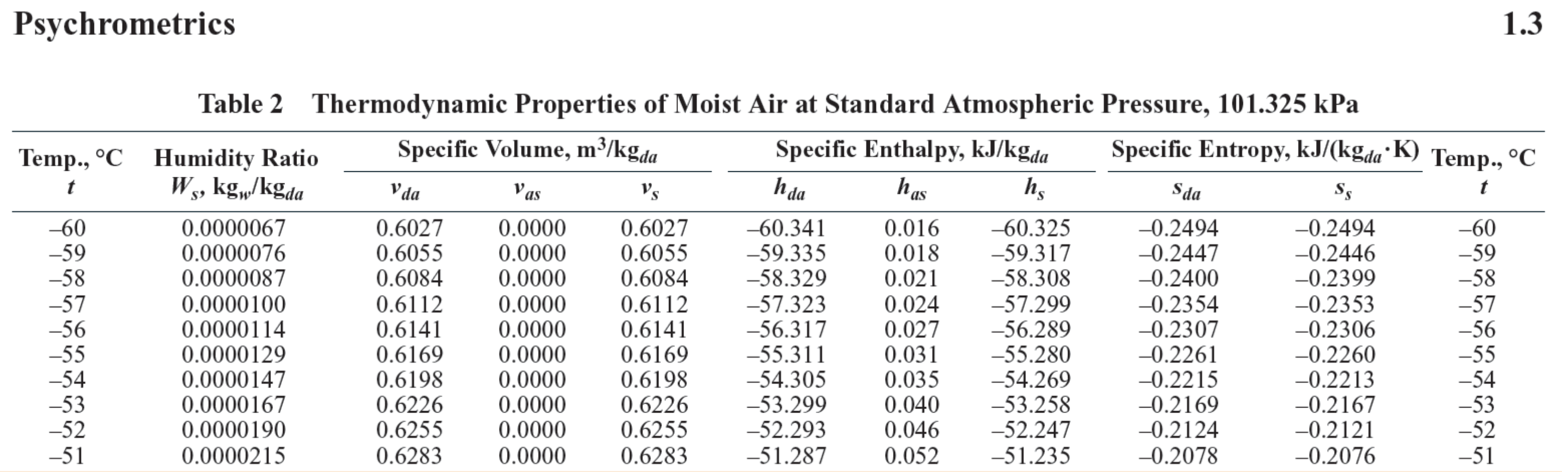
This paper is based on findings resulting from ASHRAE Research Project RP-1485.

This research updates the modeling of moist air as a real gas mixture using the virial equation of state. It includes the Hyland and Wexler model (1983a, 1983b) and considers the Nelson-Sauer model (2002). All new National Institute of Standards and Technology reference equations and the latest International Association for the Properties of Water and Steam (IAPWS) standards, as well as the current values for the molar masses and gas constants, have

New Moist Air Table in the 2009 *ASHRAE Handbook of Fundamentals*



Psychrometrics **1.3**

Table 2 Thermodynamic Properties of Moist Air at Standard Atmospheric Pressure, 101.325 kPa

Temp., °C	Humidity Ratio	Specific Volume, m^3/kg_{da}			Specific Enthalpy, kJ/kg_{da}			Specific Entropy, $kJ/(kg_{da} \cdot K)$		Temp., °C
t	W_s, kg_w/kg_{da}	v_{da}	v_{as}	v_s	h_{da}	h_{as}	h_s	s_{da}	s_s	t
–60	0.0000067	0.6027	0.0000	0.6027	–60.341	0.016	–60.325	–0.2494	–0.2494	–60
–59	0.0000076	0.6055	0.0000	0.6055	–59.335	0.018	–59.317	–0.2447	–0.2446	–59
–58	0.0000087	0.6084	0.0000	0.6084	–58.329	0.021	–58.308	–0.2400	–0.2399	–58
–57	0.0000100	0.6112	0.0000	0.6112	–57.323	0.024	–57.299	–0.2354	–0.2353	–57
–56	0.0000114	0.6141	0.0000	0.6141	–56.317	0.027	–56.289	–0.2307	–0.2306	–56
–55	0.0000129	0.6169	0.0000	0.6169	–55.311	0.031	–55.280	–0.2261	–0.2260	–55
–54	0.0000147	0.6198	0.0000	0.6198	–54.305	0.035	–54.269	–0.2215	–0.2213	–54
–53	0.0000167	0.6226	0.0000	0.6226	–53.299	0.040	–53.258	–0.2169	–0.2167	–53
–52	0.0000190	0.6255	0.0000	0.6255	–52.293	0.046	–52.247	–0.2124	–0.2121	–52
–51	0.0000215	0.6283	0.0000	0.6283	–51.287	0.052	–51.235	–0.2078	–0.2076	–51

Results

Property Library ASHRAE-LibHuAirProp

- The property library LibHuAirProp for real moist air has been developed based on the results of the RP-1485
- The property values of 2009 ASHRAE Handbook of Fundamentals Tables 2 and 3 are exactly calculated using LibHuAirProp
- Property values can be calculated for your actual barometric pressure in I-P and SI units
- Easy to use property functions in Excel®, MATLAB®, and Mathcad®
- Greater range of validity in comparison with other programs, e.g., MoistAirTab
- Properties of unsaturated, saturated moist air, and supersaturated moist air (liquid fog and ice fog) can be calculated
- Transport properties are included
- All newest IAPWS standards and NIST reference equations are used

Possible user's of spreadsheet add-in functions:

Consulting engineers or scientists in their daily work

Research & Development in companies

Universities

Conclusions

- All aims of ASHRAE RP-1485 were satisfied
- Tables 2 and 3 of the 2009 *ASHRAE Handbook of Fundamentals* were updated (first update since 1985)
- Detailed documentation of all used algorithms within the Final Report
- Research paper in the ASHRAE Journal *HVAC&R Research*
- The Property Library ASHRAE-LibHuAirProp has been developed based on the results of RP-1485
- 60 spreadsheet add-in functions are available now

Going Forward

- New algorithms for the third molar cross-virial coefficients are needed
- The GERG-2004 Equation developed for natural gases should be considered in further research

The slides are available at *www.kretzschmar-consulting-engineers.com* under "Presentations and Posters" at No. 77.