User’s Guide

for

LibHuAirProp

Library for the Calculation of Psychrometric,
Thermodynamic, and Transport Properties
for *Real* Humid Air, Steam, Water, and Ice

I-P & SI Units

Version 10.0

FluidMAT for Mathcad

Add-On for the comfortable use
of LibHuAirProp in Mathcad

Based on ASHRAE Research Projects
RP-1485 and RP-1767

Prepared by
THERMO
FLUID
PROPERTIES
www.thermofluidprop.com

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LibHuAirProp Product Information

Do you need property values for moist air in I-P or SI units in your daily work?

► Use the property library LibHuAirProp ◄

Do you need these properties in Excel®, MATLAB®, Mathcad®, Mathcad Prime®, Engineering Equation Solver®, LabVIEW™, DYMOLA®, or SimulationX®?

► Use the add-ins FluidEXL, FluidLAB, FluidMAT, FluidPRIME, FluidEES, FluidVIEW, or FluidDYM ◄

What properties can be calculated using this software?

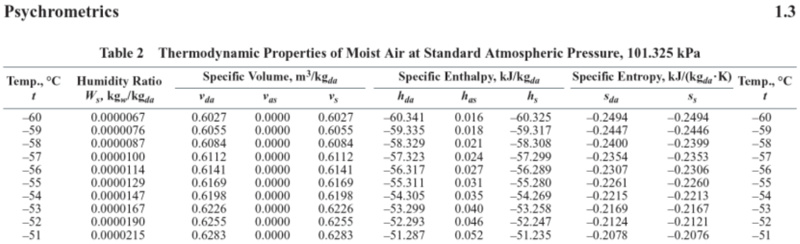
► thermodynamic properties psychrometric functions ◄
► transport properties backward functions ◄

What range of state is covered by this property library?

► unsaturated and saturated moist air ◄
► supersaturated moist air (liquid fog and ice fog) ◄
► temperatures from −143.15°C (−225.67°F) to 350°C (662°F) ◄
► pressures from 0.01 kPa (0.00145 psi) to 10,000 kPa (1450.4 psi) ◄

What are the references of LibHuAirProp?

Tables for moist air properties in the 2009, 2013, 2017, 2021, and 2025 *ASHRAE Handbook of Fundamentals* were calculated using LibHuAirProp

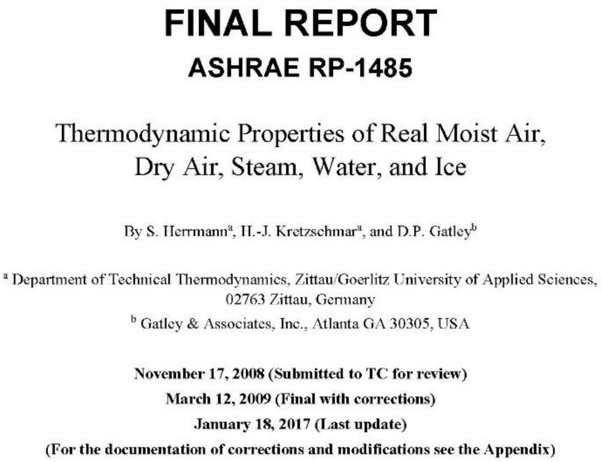


Psychrometrics 1.3

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

Temp., °C	Humidity Ratio	Specific Volume, m³/kg$_{da}$			Specific Enthalpy, kJ/kg$_{da}$			Specific Entropy, kJ/(kg$_{da}$·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

Thermodynamic and psychrometric property algorithms from ASHRAE Research Project 1485



FINAL REPORT
ASHRAE RP-1485

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

By S. Herrmann[a], H.-J. Kretzschmar[a], and D.P. Gatley[b]

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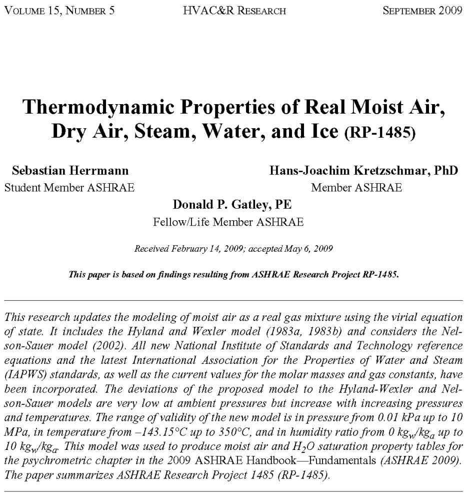
November 17, 2008 (Submitted to TC for review)
March 12, 2009 (Final with corrections)
January 18, 2017 (Last update)
(For the documentation of corrections and modifications see the Appendix)



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

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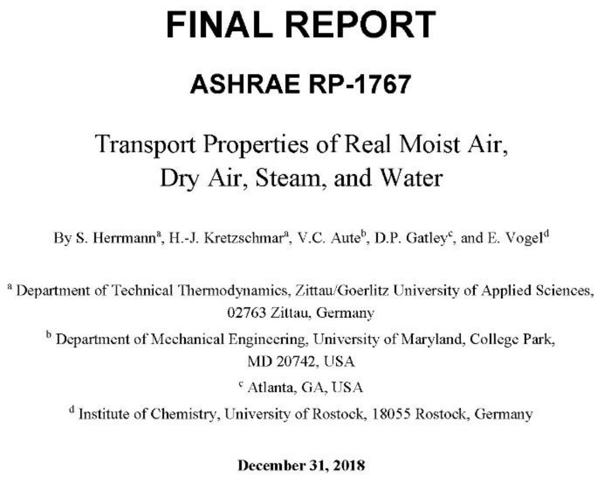
Received February 14, 2009; accepted May 6, 2009

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 been incorporated. The deviations of the proposed model to the Hyland-Wexler and Nelson-Sauer models are very low at ambient pressures but increase with increasing pressures and temperatures. The range of validity of the new model is in pressure from 0.01 kPa up to 10 MPa, in temperature from –143.15°C up to 350°C, and in humidity ratio from 0 kg$_w$/kg$_a$ up to 10 kg$_w$/kg$_a$. This model was used to produce moist air and H_2O saturation property tables for the psychrometric chapter in the 2009 ASHRAE Handbook—Fundamentals *(ASHRAE 2009). The paper summarizes ASHRAE Research Project 1485 (RP-1485).*

Transport property algorithms of moist air from ASHRAE Research Project 1767



FINAL REPORT

ASHRAE RP-1767

Transport Properties of Real Moist Air,
Dry Air, Steam, and Water

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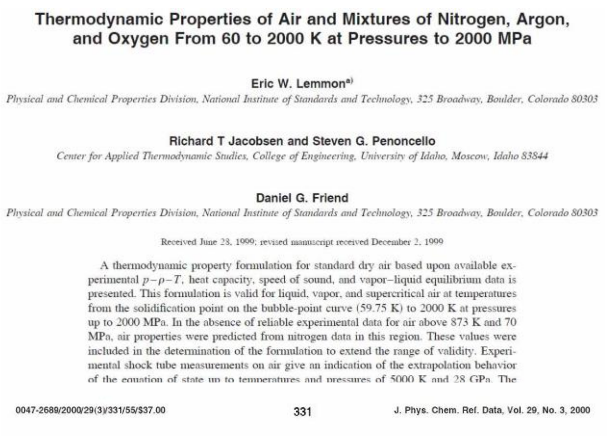
December 31, 2018

Properties of dry air from the NIST Reference Equation of *Lemmon et al.* and properties of steam, water, and ice from the Industrial Formulation IAPWS-IF97, the Scientific Formulation IAPWS-95, and other current IAPWS formulations



Thermodynamic Properties of Air and Mixtures of Nitrogen, Argon, and Oxygen From 60 to 2000 K at Pressures to 2000 MPa

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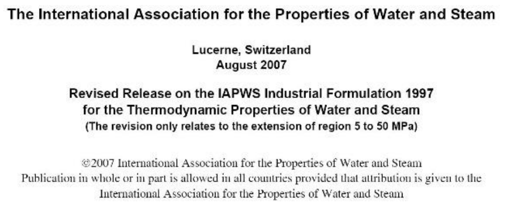
Received June 28, 1999; revised manuscript received December 2, 1999

A thermodynamic property formulation for standard dry air based upon available experimental $p-\rho-T$, heat capacity, speed of sound, and vapor–liquid equilibrium data is presented. This formulation is valid for liquid, vapor, and supercritical air at temperatures from the solidification point on the bubble-point curve (59.75 K) to 2000 K at pressures up to 2000 MPa. In the absence of reliable experimental data for air above 873 K and 70 MPa, air properties were predicted from nitrogen data in this region. These values were included in the determination of the formulation to extend the range of validity. Experimental shock tube measurements on air give an indication of the extrapolation behavior of the equation of state up to temperatures and pressures of 5000 K and 28 GPa. The

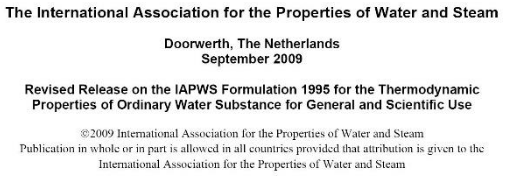
0047-2689/2000/29(3)/331/55/$37.00 331 J. Phys. Chem. Ref. Data, Vol. 29, No. 3, 2000



The International Association for the Properties of Water and Steam

Lucerne, Switzerland
August 2007

Revised Release on the IAPWS Industrial Formulation 1997
for the Thermodynamic Properties of Water and Steam
(The revision only relates to the extension of region 5 to 50 MPa)



The International Association for the Properties of Water and Steam

Doorwerth, The Netherlands
September 2009

Revised Release on the IAPWS Formulation 1995 for the Thermodynamic
Properties of Ordinary Water Substance for General and Scientific Use

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Property Library for *Real* Humid Air, Steam, Water, and Ice

ASHRAE LibHuAirProp

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0 Package Contents

Add-On for Mathcad®

The following ZIP file is delivered for your computer running Mathcad®.

ZIP file "CD_FluidMAT_ASHRAE_LibHuAirProp.zip" for Mathcad®

The ZIP file contains the following files:

FluidMAT_ASHRAE_LibHuAirProp_Setup.exe	Installation program for the FluidMAT Add-On for use in Mathcad®
FluidMAT_ASHRAE_LibHuAirProp_Users_Guide.pdf	User’s Guide

Part I-P Units

1 Property Library ASHRAE-LibHuAirProp-IP

1.1 Function Overview

1.1.1 Function Overview for Real Moist Air

Functional Dependence	**Function Name**	**Property or Function**	**Unit of the Result**	**Page**
$a = \mathrm{f}(p,t,W)$	a_ptW_HAP_IP	Thermal diffusivity	ft^2/s	3/2
$\alpha_\mathrm{p} = \mathrm{f}(p,t,W)$	alphap_ptW_HAP_IP	Relative pressure coefficient	1/°R	3/3
$\beta_\mathrm{p} = \mathrm{f}(p,t,W)$	betap_ptW_HAP_IP	Isothermal stress coefficient	lb/ft^3	3/4
$c = \mathrm{f}(p,t,W)$	c_ptW_HAP_IP	Speed of sound	ft/s	3/5
$c_p = \mathrm{f}(p,t,W)$	cp_ptW_HAP_IP	Specific isobaric heat capacity	Btu/(lb·°R)	3/6
$c_v = \mathrm{f}(p,t,W)$	cv_ptW_HAP_IP	Specific isochoric heat capacity	Btu/(lb·°R)	3/7
$f = \mathrm{f}(p,t)$	f_pt_HAP_IP	Enhancement factor (decimal ratio)	-	3/8
$h = \mathrm{f}(p,t,W)$	h_ptW_HAP_IP	Air-specific enthalpy	Btu/lb$_a$	3/9
$\eta = \mathrm{f}(p,t,W)$	Eta_ptW_HAP_IP	Dynamic viscosity	lb·s/ft^2	3/10
$\kappa = \mathrm{f}(p,t,W)$	Kappa_ptW_HAP_IP	Isentropic exponent	-	3/11
$\lambda = \mathrm{f}(p,t,W)$	Lambda_ptW_HAP_IP	Thermal conductivity	Btu/(h·ft·°R)	3/12
$\nu = \mathrm{f}(p,t,W)$	Ny_ptW_HAP_IP	Kinematic viscosity	ft^2/s	3/13
$p = \mathrm{f}(t,s,W)$	p_tsW_HAP_IP	Pressure of humid air	psi	3/14
$p = \mathrm{f}(z_\mathrm{ele})$	p_zele_HAP_IP	Pressure of humid air from elevation	psi	3/15
$p_\mathrm{Air} = \mathrm{f}(p,t,W)$	pAIR_ptW_HAP_IP	Partial pressure of dry air in moist air	psi	3/16
$p_\mathrm{H2O} = \mathrm{f}(p,t,W)$	pH2O_ptW_HAP_IP	Partial pressure of water vapor in moist air	psi	3/17
$p_\mathrm{H2Os} = \mathrm{f}(p,t)$	pH2Os_pt_HAP_IP	Partial saturation pressure of water vapour in moist air	psi	3/18

Functional Dependence	**Function Name**	**Property or Function**	**Unit of the Result**	**Page**
$\varphi = f(p,t,W)$	phi_ptW_HAP_IP	Relative humidity (decimal ratio)	-	3/19
$Pr = f(p,t,W)$	Pr_ptW_HAP_IP	PRANDTL number	-	3/20
$\psi_{Air} = f(W)$	PsiAir_W_HAP_IP	Mole fraction of dry air in moist air	mol_a/mol	3/21
$\psi_{H2O} = f(W)$	PsiH2O_W_HAP_IP	Mole fraction of water vapor in moist air	mol_w/mol	3/22
$\rho = f(p,t,W)$	Rho_ptW_HAP_IP	Density	lb/ft^3	3/23
$s = f(p,t,W)$	s_ptW_HAP_IP	Air-specific entropy	$Btu/(lb_a \cdot °R)$	3/24
$t = f(p,h,\varphi)$	t_phphi_HAP_IP	Backward function: temperature from total pressure, air-specific enthalpy and relative humidity	°F	3/25
$t = f(p,h,W)$	t_phW_HAP_IP	Backward function: temperature from total pressure, enthalpy and humidity ratio	°F	3/26
$t = f(p,s,W)$	t_psW_HAP_IP	Backward function: temperature from total pressure, entropy and humidity ratio	°F	3/27
$t = f(p,t_{wb},W)$	t_ptwbW_HAP_IP	Backward function: temperature from total pressure, wet-bulb temperature and humidity ratio	°F	3/28
$t_d = f(p,W)$	td_pW_HAP_IP	Dew-point/frost-point temperature	°F	3/29
$t_s = f(p,p_{H2O})$	ts_ppH2O_HAP_IP	Backward function: saturation temperature of water from total pressure and partial pressure of water vapor	°F	3/30
$t_{wb} = f(p,t,W)$	twb_ptW_HAP_IP	Wet-bulb/ice-bulb temperature	°F	3/31
$u = f(p,t,W)$	u_ptW_HAP_IP	Air-specific internal energy	Btu/lb_a	3/32
$v = f(p,t,W)$	v_ptW_HAP_IP	Air-specific volume	ft^3/lb_a	3/33
$W = f(p,t,p_{H2O})$	W_ptpH2O_HAP_IP	Humidity ratio from total pressure, temperature, and partial pressure of water vapor	lb_w/lb_a	3/34
$W = f(p,t,\varphi)$	W_ptphi_HAP_IP	Humidity ratio from total pressure, temperature, and relative humidity	lb_w/lb_a	3/35
$W = f(p,t_d)$	W_ptd_HAP_IP	Humidity ratio from total pressure and dew-point temperature	lb_w/lb_a	3/36

Functional Dependence	**Function Name**	**Property or Function**	**Unit of the Result**	**Page**
$W = \mathrm{f}(p,t,t_{\mathrm{wb}})$	W_pttwb_HAP_IP	Humidity ratio from total pressure, (dry bulb) temperature, and wet-bulb temperature	$\mathrm{lb_w/lb_a}$	3/37
$W_{\mathrm{s}} = \mathrm{f}(p,t)$	Ws_pt_HAP_IP	Saturation humidity ratio	$\mathrm{lb_w/lb_a}$	3/38
$\xi_{\mathrm{Air}} = \mathrm{f}(W)$	XiAir_W_HAP_IP	Mass fraction of dry air in moist air	$\mathrm{lb_a/lb}$	3/39
$\xi_{\mathrm{H2O}} = \mathrm{f}(W)$	XiH2O_W_HAP_IP	Mass fraction of water vapor in moist air	$\mathrm{lb_w/lb}$	3/40
$Z = \mathrm{f}(p,t,W)$	Z_ptW_HAP_IP	Compression factor (decimal ratio)	-	3/41

Range of Validity of Thermodynamic Properties

Property	Range of Validity					
Pressure:	0.00145	≤	p	≤	1450.4	psi
Temperature:	–225.67	≤	t	≤	662	°F
Humidity ratio:	0	≤	W	≤	10	lb_w/lb_a
Relative humidity:	0	≤	φ	≤	1	(decimal ratio)
Dew-point temperature:	–225.67	≤	t_d	≤	662	°F
Wet-bulb temperature:	–225.67	≤	t_{wb}	≤	662	°F

Units

Symbol	Quantity	Unit
p	Pressure	psi
t	Temperature	°F
W	Humidity ratio	lb_w/lb_a (lb water / lb dry air)
φ	Relative humidity	(decimal ratio)
t_d	Dew point temperature	°F
t_{wb}	Wet bulb temperature	°F

Range of Validity of Transport Properties

Property	Range of Validity					
Pressure:	0.00145	≤	p	≤	1450.4	psi
Temperature:	–99.67	≤	t	≤	662	°F
Humidity ratio:	0	≤	W	≤	10	lb_w/lb_a
Relative humidity:	0	≤	φ	≤	1	(decimal ratio)

Molar Masses

Component	Molar Mass	Reference
Dry Air	63.859 lb/kmol	[17]
Water	39.7168998 lb/kmol	[5], [6]

Reference States

Property	Dry Air	Steam, Water, and Ice
Pressure	14.6959 psi	p_s(32.018°F) = 0.088714 psi
Temperature	32°F	32.018°F
Enthalpy	0 Btu/lb	0.00026301926 Btu/lb
Entropy	0 Btu/(lb·°R)	0 Btu/(lb·°R)

1.1.2 Function Overview for Steam and Water for Temperatures $t \geq 32°F$

Functional Dependence	Function Name	Property or Function	Unit of the Result	Page
$h_{liq} = f(p,t)$	hliq_pt_97_IP	Specific enthalpy of liquid water	Btu/lb	3/43
$h_{liq,s} = f(t)$	hliqs_t_97_IP	Specific enthalpy of saturated liquid water	Btu/lb	3/44
$h_{vap,s} = f(t)$	hvaps_t_97_IP	Specific enthalpy of saturated water vapor	Btu/lb	3/45
$p_s = f(t)$	ps_t_97_IP	Saturation pressure of water	psi	3/46
$s_{liq} = f(p,t)$	sliq_pt_97_IP	Specific entropy of liquid water	Btu/(lb·°R)	3/47
$s_{liq,s} = f(t)$	sliqs_t_97_IP	Specific entropy of saturated liquid water	Btu/(lb·°R)	3/48
$s_{vap,s} = f(t)$	svaps_t_97_IP	Specific entropy of saturated water vapor	Btu/(lb·°R)	3/49
$t_s = f(p)$	ts_p_97_IP	Saturation temperature of water	°F	3/50
$v_{liq} = f(p,t)$	vliq_pt_97_IP	Specific volume of liquid water	ft³/lb	3/51
$v_{liq,s} = f(t)$	vliqs_t_97_IP	Specific volume of saturated liquid water	ft³/lb	3/52
$v_{vap,s} = f(t)$	vvaps_t_97_IP	Specific volume of saturated water vapor	ft³/lb	3/53

Range of Validity

Property	Range of Validity					
Pressure:	0.00145	≤	*p*	≤	1450.4	psi
Temperature:	32	≤	*t*	≤	662	°F

Units

Symbol	Quantity	Unit
p	Pressure	psi
t	Temperature	°F

Reference State

Property	Water Vapor and Liquid Water
Pressure	p_s(32.018°F) = 0.088714 psi
Temperature	32.018°F
Enthalpy	0.00026301926 Btu/lb
Entropy	0 Btu/(lb·°R)

1.1.3 Function Overview for Steam and Ice for Temperatures $t \leq 32°F$

Functional Dependence	**Function Name**	**Property**	**Unit of the Result**	**Page**
$h_{ice,sub} = f(t)$	hicesub_t_06_IP	Specific enthalpy of saturated ice	Btu/lb	3/55
$h_{vap,sub} = f(t)$	hvapsub_t_95_IP	Specific enthalpy of saturated water vapor	Btu/lb	3/56
$p_{mel} = f(t)$	pmel_t_08_IP	Melting pressure of ice	psi	3/57
$p_{sub} = f(t)$	psub_t_08_IP	Sublimation pressure of ice	psi	3/58
$s_{ice,sub} = f(t)$	sicesub_t_06_IP	Specific entropy of saturated ice	Btu/(lb·°R)	3/59
$s_{vap,sub} = f(t)$	svapsub_t_95_IP	Specific entropy of saturated water vapor	Btu/(lb·°R)	3/60
$t_{mel} = f(p)$	tmel_p_08_IP	Melting temperature of ice	°F	3/61
$t_{sub} = f(p)$	tsub_p_08_IP	Sublimation temperature of ice	°F	3/62
$v_{ice,sub} = f(t)$	vicesub_t_06_IP	Specific volume of saturated ice	ft³/lb	3/63
$v_{vap,sub} = f(t)$	vvapsub_t_95_IP	Specific volume of saturated water vapor	ft³/lb	3/64

Range of Validity

Property	Range of Validity					
Pressure:	p_{sub}(–225.67°F) = 1.7407E-12	≤	*p*	≤	1450.4	psi
Temperature:	–225.67	≤	*t*	≤	32	°F

Units

Symbol	Quantity	Unit
p	Pressure	psi
t	Temperature	°F

Reference State

Property	Water Vapor and Ice
Pressure	p_s(32.018°F) = 0.088714 psi
Temperature	32.018°F
Enthalpy	0.00026301926 Btu/lb
Entropy	0 Btu/(lb·°R)

1.2 Conversion of SI and I-P Units

Property		Conversion: SI Units → I-P Units	Conversion: I-P Units → SI Units	Units SI	Units I-P
Thermal diffusivity	a	$\frac{a_{\mathrm{IP}}}{\frac{\mathrm{ft^2}}{\mathrm{s}}} = \frac{a_{\mathrm{SI}}}{\frac{\mathrm{m^2}}{\mathrm{s}}} \times 10.76391042$	$\frac{a_{\mathrm{SI}}}{\frac{\mathrm{m^2}}{\mathrm{s}}} = \frac{a_{\mathrm{IP}}}{\frac{\mathrm{ft^2}}{\mathrm{s}}} \times 0.0929304$	m²/s	ft²/s
Relative pressure coefficient	α_p	$\frac{\alpha_{p,\mathrm{IP}}}{\frac{1}{\mathrm{°R}}} = \frac{\alpha_{p,\mathrm{SI}}}{\frac{1}{\mathrm{K}}} \times \frac{9}{5}$	$\frac{\alpha_{p,\mathrm{SI}}}{\frac{1}{\mathrm{K}}} = \frac{\alpha_{p,\mathrm{IP}}}{\frac{1}{\mathrm{°R}}} \times \frac{5}{9}$	1/K	1/°R
Isothermal stress coefficient	β_p	$\frac{\beta_{p,\mathrm{IP}}}{\frac{\mathrm{lb}}{\mathrm{ft^3}}} = \frac{\beta_{p,\mathrm{SI}}}{\frac{\mathrm{kg}}{\mathrm{m^3}}} \times 0.062428$	$\frac{\beta_{p,\mathrm{SI}}}{\frac{\mathrm{kg}}{\mathrm{m^3}}} = \frac{\beta_{p,\mathrm{IP}}}{\frac{\mathrm{lb}}{\mathrm{ft^3}}} \times 16.018463$	kg/m³	lb/ft³
Speed of sound	c	$\frac{c_{\mathrm{IP}}}{\frac{\mathrm{ft}}{\mathrm{s}}} = \frac{c_{\mathrm{SI}}}{\frac{\mathrm{m}}{\mathrm{s}}} \times 3.2808399$	$\frac{c_{\mathrm{SI}}}{\frac{\mathrm{m}}{\mathrm{s}}} = \frac{c_{\mathrm{IP}}}{\frac{\mathrm{ft}}{\mathrm{s}}} \times 0.3048$	m/s	ft/s
Specific isobaric heat capacity	c_p	$\frac{c_{p,\mathrm{IP}}}{\frac{\mathrm{Btu}}{\mathrm{lb\ °R}}} = \frac{c_{p,\mathrm{SI}}}{\frac{\mathrm{kJ}}{\mathrm{kg\ K}}} \times 0.2388459$	$\frac{c_{p,\mathrm{SI}}}{\frac{\mathrm{kJ}}{\mathrm{kg\ K}}} = \frac{c_{p,\mathrm{IP}}}{\frac{\mathrm{Btu}}{\mathrm{lb\ °R}}} \times 4.1868$	kJ/(kg·K)	Btu/(lb·°R)
Specific isochoric heat capacity	c_v	$\frac{c_{v,\mathrm{IP}}}{\frac{\mathrm{Btu}}{\mathrm{lb\ °R}}} = \frac{c_{v,\mathrm{SI}}}{\frac{\mathrm{kJ}}{\mathrm{kg\ K}}} \times 0.2388459$	$\frac{c_{v,\mathrm{SI}}}{\frac{\mathrm{kJ}}{\mathrm{kg\ K}}} = \frac{c_{v,\mathrm{IP}}}{\frac{\mathrm{Btu}}{\mathrm{lb\ °R}}} \times 4.1868$	kJ/(kg·K)	Btu/(lb·°R)
Dynamic viscosity	η	$\frac{\eta_{\mathrm{IP}}}{\frac{\mathrm{lb\ s}}{\mathrm{ft^2}}} = \frac{\eta_{\mathrm{SI}}}{\frac{\mathrm{Pa}}{\mathrm{s}}} \times 0.02088543$	$\frac{\eta_{\mathrm{SI}}}{\frac{\mathrm{Pa}}{\mathrm{s}}} = \frac{\eta_{\mathrm{IP}}}{\frac{\mathrm{lb\ s}}{\mathrm{ft^2}}} \times 47.880259$	Pa·s	lb·s/ft²
Enhancement factor	f	$f_{\mathrm{IP}} = f_{\mathrm{SI}}$	$f_{\mathrm{SI}} = f_{\mathrm{IP}}$	-	-

Property		**Conversion: SI Units → I-P Units**	**Conversion: I-P Units → SI Units**	**Units SI**	**Units I-P**
Air-specific enthalpy (moist air)	h	$\frac{h_{IP}}{\frac{Btu}{lb_a}} = \frac{h_{SI}}{\frac{kJ}{kg_a}} \times 0.4299226 + 7.68565365666$	$\frac{h_{SI}}{\frac{kJ}{kg_a}} = \left(\frac{h_{IP}}{\frac{Btu}{lb_a}} - 7.68565365666 \right) \times 2.326$	kJ/kg_a	Btu/lb_a
Specific enthalpy (water, water vapor, ice)	h_w	$\frac{h_{IP}}{\frac{Btu}{lb}} = \frac{h_{SI}}{\frac{kJ}{kg}} \times 0.4299226$	$\frac{h_{SI}}{\frac{kJ}{kg}} = \frac{h_{IP}}{\frac{Btu}{lb}} \times 2.326$	kJ/kg	Btu/lb
Isentropic exponent	κ	$\kappa_{IP} = \kappa_{SI}$	$\kappa_{SI} = \kappa_{IP}$	-	-
Thermal conductivity	λ	$\frac{\lambda_{IP}}{\frac{Btu}{h\ ft\ °R}} = \frac{\lambda_{SI}}{\frac{W}{m\ K}} \times 0.57778932$	$\frac{\lambda_{SI}}{\frac{W}{m\ K}} = \frac{\lambda_{IP}}{\frac{Btu}{h\ ft\ °R}} \times 1.73073467$	W/(m·K)	Btu/(h·ft·°R)
Kinematic viscosity	ν	$\frac{\nu_{IP}}{\frac{ft^2}{s}} = \frac{\nu_{SI}}{\frac{m^2}{s}} \times 10.763910417$	$\frac{\nu_{SI}}{\frac{m^2}{s}} = \frac{\nu_{IP}}{\frac{ft^2}{s}} \times 0.092903040$	m^2/s	ft^2/s
Pressure	p	$\frac{p_{IP}}{psi} = \frac{p_{SI}}{kPa} \times 0.14503774$	$\frac{p_{SI}}{kPa} = \frac{p_{IP}}{psi} \times 6.894757$	kPa	psi
Relative humidity	φ	$\varphi_{IP} = \varphi_{SI}$	$\varphi_{SI} = \varphi_{IP}$	-	-
Prandtl number	Pr	$Pr_{IP} = Pr_{IP}$	$Pr_{SI} = Pr_{IP}$	-	-
Mole fraction	ψ	$\psi_{IP} = \psi_{SI}$	$\psi_{SI} = \psi_{IP}$	mol/mol	mol/mol
Density	ρ	$\frac{\rho_{IP}}{\frac{lb}{ft^3}} = \frac{\rho_{SI}}{\frac{kg}{m^3}} \times 0.062428$	$\frac{\rho_{SI}}{\frac{kg}{m^3}} = \frac{\rho_{IP}}{\frac{lb}{ft^3}} \times 16.018463$	kg/m^3	lb/ft^3
Air-specific entropy (moist air)	s	$\frac{s_{IP}}{\frac{Btu}{lb_a\ °R}} = \frac{s_{SI}}{\frac{kJ}{kg_a\ K}} \times 0.2388459 + 0.01616365106$	$\frac{s_{SI}}{\frac{kJ}{kg_a\ K}} = \left(\frac{s_{IP}}{\frac{Btu}{lb_a\ °R}} - 0.01616365106 \right) \times 4.1868$	$kJ/(kg_a \cdot K)$	$Btu/(lb_a \cdot °R)$

Property		Conversion: SI Units → I-P Units	Conversion: I-P Units→ SI Units	Units SI	Units I-P
Specific entropy (water, water vapor, ice)	s_w	$\frac{s_{IP}}{\frac{Btu}{lb_a\ °R}} = \frac{s_{SI}}{\frac{kJ}{kg_a\ K}} \times 0.23884589$	$\frac{s_{SI}}{\frac{kJ}{kg_a\ K}} = \frac{s_{IP}}{\frac{Btu}{lb_a\ °R}} \times 4.1868$	$kJ/(kg_a \cdot K)$	$Btu/(lb_a \cdot °R)$
Temperature	t	$\frac{t_{IP}}{°F} = \frac{t_{SI}}{°C} \times \frac{9}{5} + 32$	$\frac{t_{SI}}{°C} = \left(\frac{t_{IP}}{°F} - 32\right) \times \frac{5}{9}$	°C	°F
Air-specific internal energy (moist air)	u	$(u = h - pv)$ $\frac{u_{IP}}{\frac{Btu}{lb_a}} = \frac{h_{SI}}{\frac{kJ}{kg_a}} \times 0.4299226 + 7.68565365666 - \frac{p_{SI}}{kPa} \times 0.145037738 \cdot \frac{v_{SI}}{\frac{m^3}{kg_a}} \times 16.018453$	$(u = h - pv)$ $\frac{u_{SI}}{\frac{kJ}{kg_a}} = \left(\frac{h_{IP}}{\frac{Btu}{lb_a}} - 7.68565365666\right) \times 2.236 - \frac{p_{IP}}{psi} \times 6.894757293 \cdot \frac{v_{SIP}}{\frac{ft^3}{lb_a}} \times 0.062428$	kJ/kg_a	Btu/lb_a
Air-specific volume (moist air)	v	$\frac{v_{IP}}{\frac{ft^3}{lb_a}} = \frac{v_{SI}}{\frac{m^3}{kg_a}} \times 16.018453$	$\frac{v_{SI}}{\frac{m^3}{kg_a}} = \frac{v_{IP}}{\frac{ft^3}{lb_a}} \times 0.062428$	m^3/kg_a	ft^3/lb_a
Specific volume (water, water vapor, ice)	v_W	$\frac{v_{IP}}{\frac{ft^3}{lb}} = \frac{v_{SI}}{\frac{m^3}{kg}} \times 16.018453$	$\frac{v_{SI}}{\frac{m^3}{kg}} = \frac{v_{IP}}{\frac{ft^3}{lb}} \times 0.062428$	m^3/kg	ft^3/lb
Humidity ratio	W	$W_{IP} = W_{SI}$	$W_{SI} = W_{IP}$	kg_w/kg_a	lb_w/lb_a
Mass fraction	ξ	$\xi_{IP} = \xi_{SI}$	$\xi_{SI} = \xi_{IP}$	kg_w/kg	lb_w/lb
Compression factor	Z	$Z_{IP} = Z_{SI}$	$Z_{SI} = Z_{IP}$	-	-

1.3 Calculation Algorithms

1.3.1 Algorithms for Real Moist Air

The properties of moist air are calculated from the modified Hyland-Wexler model given in Herrmann, Kretzschmar, and Gatley (HKG) [1], [2]. The modifications incorporate:

- the value for the universal molar gas constant from the CODATA standard by Mohr and Taylor [22]
- the value for the molar mass of dry air from Gatley et al. [17] and that of water from IAPWS-95 [5], [6]
- the calculation of the ideal-gas parts of the heat capacity, enthalpy, and entropy for dry air from the fundamental equation of Lemmon et al. [14]
- the calculation of the ideal-gas parts of the heat capacity, enthalpy, and entropy for water vapor from IAPWS-IF97 [7], [8], [9] for $t \geq 32°\mathrm{F}$ and from IAPWS-95 [5], [6] for $t \leq 32°\mathrm{F}$
- the calculation of the vapor-pressure enhancement factor from the equation given by the models of Hyland and Wexler [21]
- the 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. [14] according to Feistel et al. [24]
- the calculation of the second and third molar virial coefficients B_{ww} and C_{www} for water and steam from IAPWS-95 [5], [6] according to Feistel et al. [24]
- the calculation of the air-water second molar cross-virial coefficient B_{aw} from Harvey and Huang [15]
- the calculation of the air-water third molar cross-virial coefficients C_{aaw} and C_{aww} from Nelson and Sauer [12], [13]
- the calculation of the saturation pressure of water from IAPWS-IF97 [7], [8], [9] for $t \geq 32°\mathrm{F}$ and of the sublimation pressure of water from IAPWS-08 [11] for $t \leq 32°\mathrm{F}$
- the calculation of the isothermal compressibility of saturated liquid water from IAPWS-IF97 [7], [8], [9] for $t \geq 32°\mathrm{F}$ and that of ice from IAPWS-06 [10] for $t \leq 32°\mathrm{F}$ in the determination of the vapor-pressure enhancement factor
- the calculation of Henry's constant from the IAPWS Guideline 2004 [16] in the determination of the enhancement factor. The mole fractions for the three main components of dry air were taken from Lemmon et al. [14]. Argon was not considered in the calculation of Henry’s constant in the former research projects, but it is now the third component of dry air.

The transport properties of moist air are calculated from the model given in Herrmann et al. [3], [4].

1.3.2 Algorithms for Steam and Water for Temperatures $t \geq 32°F$

The *p*-*T* diagram in Fig. 1 shows the formulations used for water and water vapor. The temperature range above 32°F is covered by IAPWS-IF97 [7], [8], [9]:

- The saturation line is calculated from the IAPWS-IF97 saturation pressure equation $p_s^{97}(t)$ and saturation temperature equation $t_s^{97}(p)$.
- The properties in the liquid region including saturated-liquid line are calculated from the fundamental equation of the IAPWS-IF97 region 1.
- The properties in the vapor region including saturated-vapor line are calculated from the fundamental equation of the IAPWS-IF97 region 2.

1.3.3 Algorithms for Steam and Ice for Temperatures $t \leq 32°F$

- The sublimation curve is covered by the IAPWS-08 sublimation pressure equation $p_{\text{subl}}^{08}(t)$ [11] (see Fig. 1).
- The properties of ice including saturated ice are determined by the fundamental equation of the IAPWS-06 [10].
- The properties of vapor including saturated vapor are calculated from the fundamental equation of IAPWS-95 [5], [6].

1.3.4 Overview of the Applied Formulations for Steam, Water, and Ice

The following *p*-*T* diagram shows the used IAPWS Formulations and the ranges where they are applied.

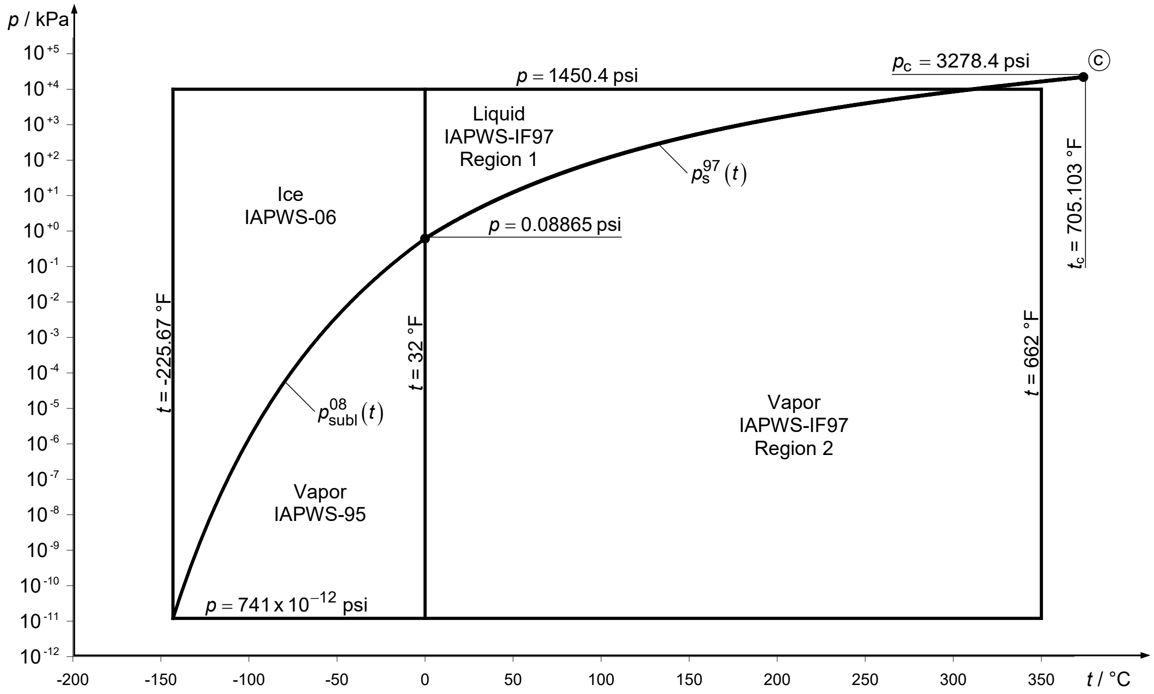


Figure 1: *p*-*T* diagram with used IAPWS formulations for steam, water, and ice.

2 Add-On FluidMAT Mathcad® for ASHRAE-LibHuAirProp-IP

2.1 Installing FluidMAT including LibHuAirProp

The FluidMAT Add-On has been developed to calculate thermodynamic properties in Mathcad® more conveniently.

Within Mathcad® it enables the direct access to functions relating to real moist air, steam, water, and ice from the ASHRAE-LibHuAirProp-IP property library.

This section describes the installation of both FluidMAT LibHuAirProp_IP and LibHuAirProp_SI.

Before you begin, it is best to close any Windows® applications, since Windows® may need to be rebooted during the installation process.

After you have downloaded and extracted the zip-file "CD_FluidMAT_ASHRAE_LibHuAirProp.zip", you will see the folder

CD_FluidMAT_ASHRAE_LibHuAirProp

in your Windows Explorer®, Norton Commander® etc.

Now, open this folder by double-clicking on it.

Within this folder you will see the following files:

FluidMAT_ASHRAE_LibHuAirProp_Users_Guide.pdf
FluidMAT_LibHuAirProp_Setup.exe.

In order to run the installation of FluidMAT, including the ASHRAE-LibHuAirProp property library, double-click on the file

FluidMAT_ASHRAE_LibHuAirProp_Setup.exe.

Installation may start with a window noting that all Windows® programs should be closed.

When this is the case, the installation can be continued. Click the "Next >" button.

The Read-Me file window will give you information about the FluidMAT product. Click "Next >" to leave this window.

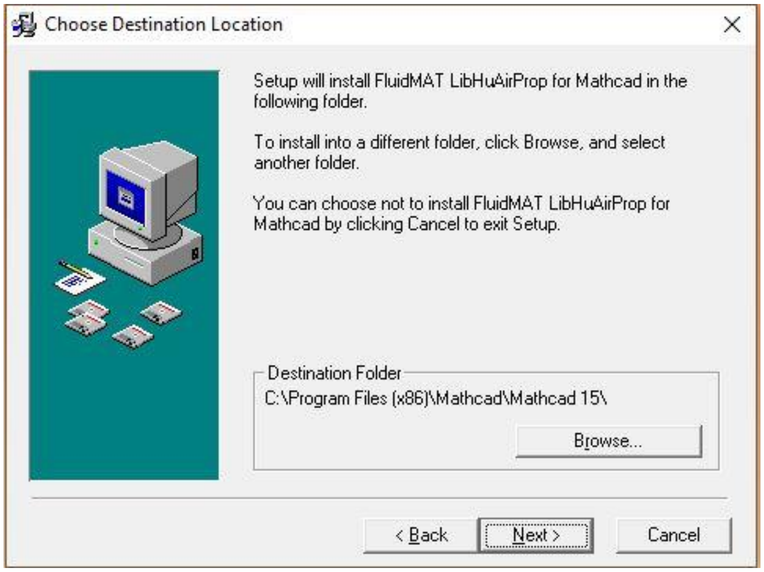
In the following dialog box, "Choose Destination Location" (see Figure 2.1.1), the default path where Mathcad® has been installed will be shown:

C:\Program Files (x86)\Mathcad\Mathcad 15\.

By clicking the "Browse…" button, you can change the installation directory before installation.

The path will be displayed in the window.

I-P – 2/2



Setup will install FluidMAT LibHuAirProp for Mathcad in the following folder.

To install into a different folder, click Browse, and select another folder.

You can choose not to install FluidMAT LibHuAirProp for Mathcad by clicking Cancel to exit Setup.

Destination Folder

C:\Program Files (x86)\Mathcad\Mathcad 15\

Figure 2.1.1: "Choose Destination Location"

Click on "Next >" in the window "Choose Destination Location".

Click on the "Next >" button in the "Start Installation" window.

After FluidMAT LibHuAirProp has been installed, the sentence "FluidMAT LibHuAirProp has been successfully installed" will be shown.

Confirm this by clicking the "Finish >" button.

During the installation process the following files are copied into the chosen destination folder (the same folder where Mathcad® was initially installed in):

INSTALL_MAT_LibHuAirProp.LOG	Installation log-file
LC.dll	Dynamic link library for use in Windows® programs
LibHuAirProp_IP.dll	Property library for real moist air
LibHuAirProp_SI.dll	Property library for real moist air
Readme_MAT_LibHuAirProp.txt	ReadMe file

The following files were installed into your Mathcad® subdirectory \userEFI:

MAT_LibHuAirProp_IP.dll	Function definition of LibHuAirProp-IP
MAT_LibHuAirProp_SI.dll	Function definition of LibHuAirProp-SI

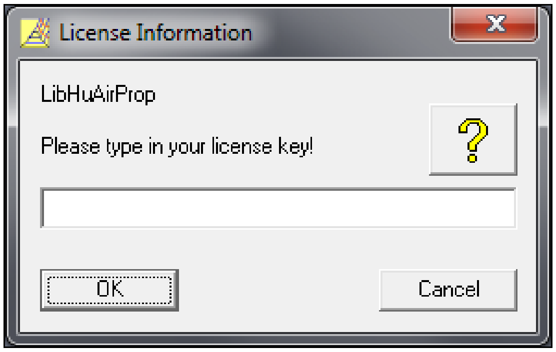
The following files were installed into your Mathcad® subdirectory \doc\funcdoc:

MAT_LibHuAirProp_IP.xml	Function registration in the dialog window "Insert Function" for LibHuAirProp-IP (Mathcad® version 11 or lower)
MAT_LibHuAirProp_IP_DE.xml	Function registration in the dialog window "Insert Function" for LibHuAirProp-IP (German Mathcad® version 12 or higher)
MAT_LibHuAirProp_IP_EN.xml	Function registration in the dialog window "Insert Function" for LibHuAirProp-IP (English Mathcad® version 12 or higher)
MAT_LibHuAirProp_SI.xml	Function registration in the dialog window "Insert Function" for LibHuAirProp-SI (Mathcad® version 11 or lower)
MAT_LibHuAirProp_SI_DE.xml	Function registration in the dialog window "Insert Function" for LibHuAirProp-SI (German Mathcad® version 12 or higher)
MAT_LibHuAirProp_SI_EN.xml	Function registration in the dialog window "Insert Function" for LibHuAirProp-SI (English Mathcad® version 12 or higher)

From within Mathcad® you can now select the ASHRAE-LibHuAirProp property functions.

2.2 Licensing the LibHuAirProp Property Library

The licensing procedure has to be carried out when you are calculating a function with LibHuAirProp in Mathcad® and a FluidMAT prompt message appears. In this case, you will see the "License Information" window for LibHuAirProp (see figure below).



License Information

LibHuAirProp

Please type in your license key!

Figure 2.2.1: "License Information" window

Here you are asked to type in the license key which you have obtained from Kretzschmar Consulting Engineers. If you do not have this, or have any questions, you will find contact information on the "Content" page of this User's Guide or by clicking the yellow question mark in the "License Information" window.

If you do not enter a valid license it is still possible to use Mathcad® by clicking "Cancel". In this case, the LibHuAirProp property library will display the result "–11111111" for every calculation.

The "License Information" window will appear every time you use FluidMAT LibHuAirProp until you enter a license code to complete registration. If you decide not to use FluidMAT LibHuAirProp, you can uninstall the program following the instructions given in section 2.4 of this User's Guide.

With this procedure both the LibHuAirProp-SI and LibHuAirProp-IP property libraries have been licensed.

2.3 Example: Calculation of $h = f(p,t,W)$

Now we will calculate, step by step, the air-specific enthalpy h as a function of pressure p, temperature t and humidity ratio W of moist air using FluidMAT.

Please carry out the following steps:

- Start Mathcad®.

Type "p:" and enter the value for pressure p in psi
(Range of validity: p = 0.00145 … 1450.4 psi)

⇒ e.g.: Enter "p:14.6959", then press the tabulator key and enter "in psi".

Note:

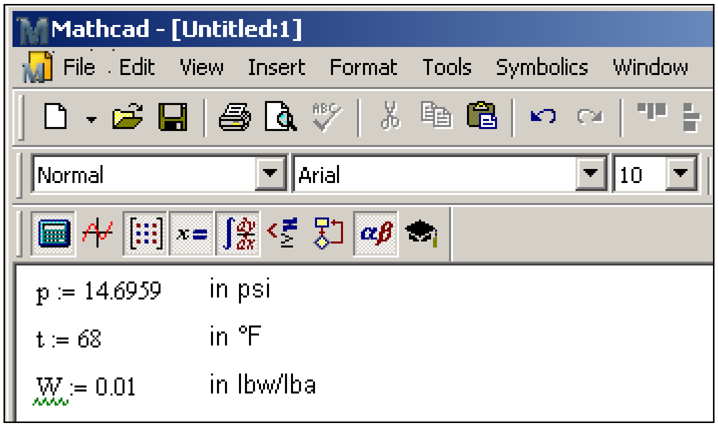
When typing in the comment containing the unit of the input parameter, Mathcad® switches into the text mode, since you type in a space using the space bar, e.g. "in<space>psi". The text modus is marked by a red cursor instead of a blue one in the math mode. After typing a comment, always finish by positioning the mouse pointer below the variable typed in before and clicking the left mouse button to switch back to math mode.

- Type "t:" and enter the value for temperature t in °F
  (Range of validity: t = –226.67 ... 662 °F)

  ⇒ e.g.: Enter "t:68", then press the tabulator key and enter "in °F".
- Type "W:" and enter the value for the humidity ratio W in lb_w/lb_a (*lb water* per *lb air*)
  (Range of validity: W = 0 … 10 lb_w/lb_a)

  ⇒ e.g.: Enter "W:0.01", then press the tabulator key and enter "in lbw/lba".

The Mathcad® sheet should now look as shown in Figure 2.3.1.



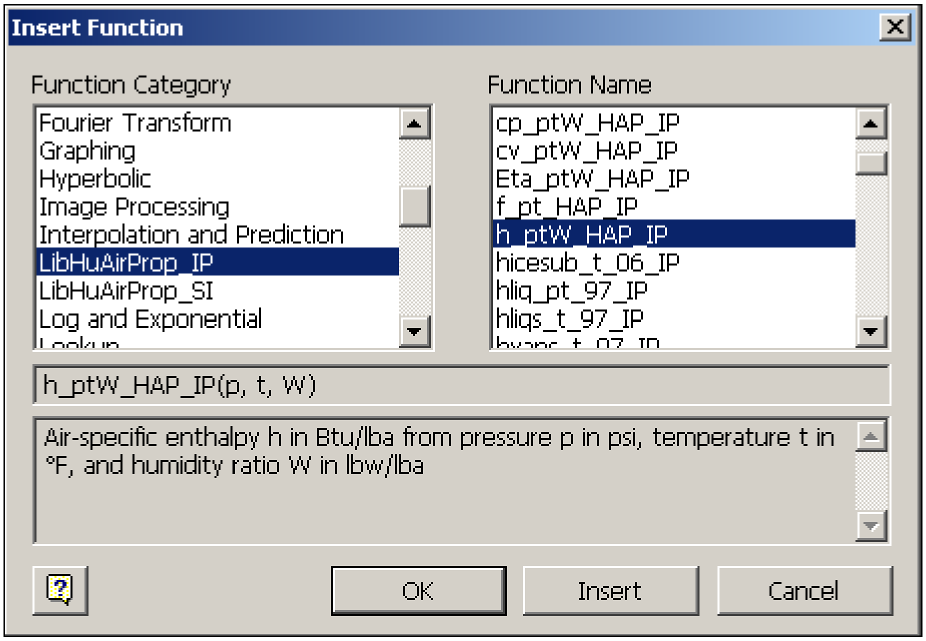
p := 14.6959 in psi

t := 68 in °F

W := 0.01 in lbw/lba

Figure 2.3.1: Example Mathcad® sheet after input of the given parameters

- Enter the symbol for the result and then a colon
  ⇒ e.g.: Type "h:".
- Now, click "Insert" in the Mathcad® menu bar and then "Function…"
  The "Insert Function" window appears (see Figure 2.3.2)
- Click "LibHuAirProp_IP" under "Function Category" on the left hand side
  (see Figure 2.3.2)
- Choose "h_ptW_HAP_IP" under "Function Name" on the right hand side

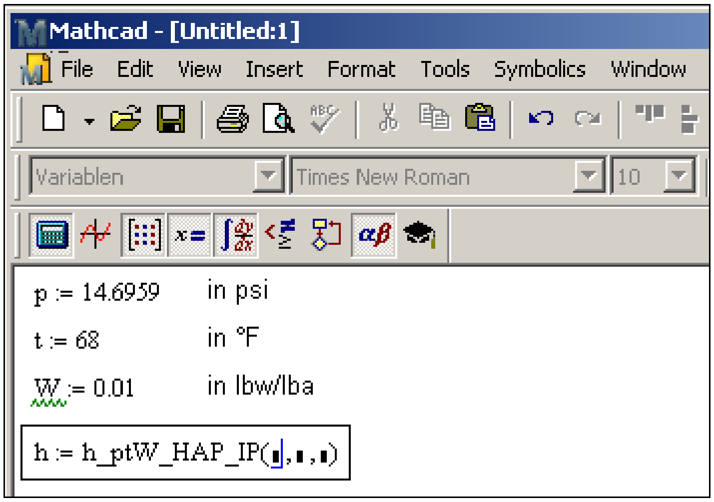


h_ptW_HAP_IP(p, t, W)

Air-specific enthalpy h in Btu/lba from pressure p in psi, temperature t in °F, and humidity ratio W in lbw/lba

Figure 2.3.2: Choice of library and function name

- Click the "OK" button.
  Now you will see the line "**h_ptW_HAP_IP(■,■,■)**" in the Mathcad$^{®}$ window (see Figure 2.3.3).



p := 14.6959 in psi

t := 68 in °F

W := 0.01 in lbw/lba

h := h_ptW_HAP_IP(■,■,■)

Figure 2.3.3: Example Mathcad$^{®}$ sheet with formula and placeholders

- The cursor is now situated on the first operand. You can now enter the value for *p* either by entering the value directly or by entering the name of the variable where the value was saved.

  ⇒ e.g.: Enter "p".

- Situate the cursor on the next placeholder. You can now enter the value for the temperature *t* either by entering the value for *t* directly or by typing the name of the variable in which the value of the temperature has been saved.

  ⇒ e.g.: Enter "t".

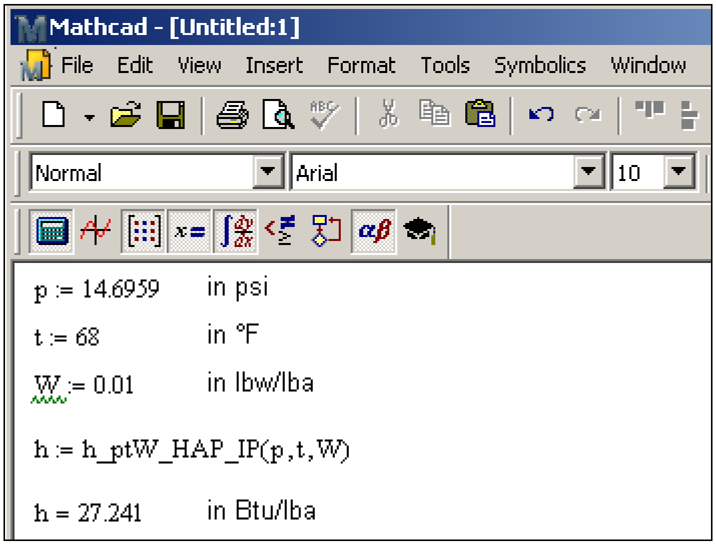
- Situate the cursor on the next placeholder. You can now enter the value for the humidity ratio *W* either by entering the value for *W* directly or by typing the name of the variable in which the value of the humidity ratio has been saved.

  ⇒ e.g.: Enter "W".

- Close the input formula by pressing the "Enter" key.
- You can now go on working with the variable *h* which we have just calculated, or you can have the result for this calculated. If you wish to see the result, type the command **"h="** on the next line in the Mathcad® window.
- The result for *h* in Btu/lb$_a$ appears. To add the unit, press the tabulator key twice and enter "in Btu/lba".

  ⇒ The result in our sample calculation here is: h = 27.241 Btu/lb$_a$.

  The representation of the result depends on the number of decimal places which you have set in Mathcad®.



p := 14.6959 in psi

t := 68 in °F

W := 0.01 in lbw/lba

h := h_ptW_HAP_IP(p,t,W)

h = 27.241 in Btu/lba

Figure 2.3.4: Example Mathcad® sheet with finished calculation

The calculation of *h* = f(*p*,*t*,*W*) has been carried out.

You can now arbitrarily change the values for *p*, *t*, and *W*. The air-specific enthalpy is recalculated and updated every time you change the data. This shows that the Mathcad® data flow and the DLL calculations are working together successfully.

2.4 Removing FluidMAT including LibHuAirProp

To remove FluidMAT ASHRAE-LibHuAirProp from Mathcad® and your hard drive, carry out the following steps:

- Click the "Start" button in the Windows® task bar
- Click "Settings"
- Click "Control Panel"
- Double click "Add or Remove Programs"
- Click on "FluidMAT LibHuAirProp" in the list box
- Click the "Add or Remove" button
- Mark "Automatic" and click the "Next >" button
- Click "Finish" in the "Perform Uninstall" window

Finally, close the "Add or Remove Programs" and "Control Panel" windows.

Now FluidMAT ASHRAE-LibHuAirProp has been removed.

3 Property Functions of ASHRAE-LibHuAirProp-IP

3.1 Functions for Real Moist Air

Thermal Diffusivity a = f(p,t,W)

Function Name:

a_ptW_HAP_IP

Fortran Program:

REAL*8 FUNCTION A_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in psi
t - Temperature t in °F
W - Humidity ratio W in $\mathrm{lb_w/lb_a}$

Result:

a_ptW_HAP_IP - Thermal diffusivity of humid air in $\mathrm{ft^2/s}$

Range of Validity:

Temperature t:	from -99.67°F to 662°F
Total pressure p:	from 0.00145 psi to 1450.4 psi
Humidity ratio W:	$0 \le W \le W_\mathrm{s}$

Comments:

- Thermal diffusivity $a = \dfrac{\lambda}{\rho \cdot c_p}$
- Calculation for supersaturated humid air ($W > W_\mathrm{s}$) is not possible

Result for Wrong Input Values:

a_ptW_HAP_IP = -1000

References:

$\lambda(p,t,W)$	Herrmann et al. [3], [4]
$\rho(p,t,W)$	Herrmann et al. [1], [2]
$c_p(p,t,W)$	Herrmann et al. [1], [2]

Relative Pressure Coefficient α_p = f(p,t,W)

Function Name:

alphap_ptW_HAP_IP

Fortran Program:

REAL*8 FUNCTION ALPHAP_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in psi
t - Temperature t in °F
W - Humidity ratio W in $\mathrm{lb_w/lb_a}$

Result:

alphap_ptW_HAP_IP - Relative pressure coefficient of humid air in 1/°R

Range of Validity:

Temperature t:	from -225.67°F to 662°F
Total pressure p:	from 0.00145 psi to 1450.4 psi
Humidity ratio W:	$0 \le W \le W_s$

Comments:

- Relative pressure coefficient $\alpha_p = \frac{1}{p}\left(\frac{\partial p}{\partial T}\right)_v$
- Calculation for supersaturated humid air ($W > W_s$) is not possible

Result for Wrong Input Values:

alphap_ptW_HAP_IP = -1000

References:

$\alpha_p(p,t,W)$ Herrmann et al. [1], [2]

Isothermal Stress Coefficient β_p = f(p,t,W)

Function Name:

betap_ptW_HAP_IP

Fortran Program:

REAL*8 FUNCTION BETAP_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in psi
t - Temperature t in °F
W - Humidity ratio W in $\mathrm{lb_w/lb_a}$

Result:

betap_ptW_HAP_IP - Isothermal stress coefficient of humid air in $\mathrm{lb/ft^3}$

Range of Validity:

Temperature t:	from -225.67°F to 662°F
Total pressure p:	from 0.00145 psi to 1450.4 psi
Humidity ratio W:	$0 \le W \le W_\mathrm{s}$

Comments:

- Isothermal stress coefficient $\beta_p = -\frac{1}{p}\left(\frac{\partial p}{\partial v}\right)_\mathrm{T}$
- Calculation for supersaturated humid air ($W > W_\mathrm{s}$) is not possible

Result for Wrong Input Values:

betap_ptW_HAP_IP = -1000

References:

$\beta_p(p,t,W)$ Herrmann et al. [1], [2]

Speed of Sound *c* = f(*p*,*t*,*W*)

Function Name:

c_ptW_HAP_IP

Fortran Program:

REAL*8 FUNCTION   C_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in psi
t - Temperature t in °F
W - Humidity ratio W in $\mathrm{lb_w/lb_a}$

Result:

c_ptW_HAP_IP - Speed of sound of humid air in ft/s

Range of Validity:

Temperature t:	from -225.67°F to 662°F
Total pressure p:	from 0.00145 psi to 1450.4 psi
Humidity ratio W:	$0 \le W \le 10\,\mathrm{lb_w/lb_a}$

Comments:

- Speed of sound $c = v\sqrt{-\left(\frac{\partial p}{\partial v}\right)_s}$
- When calculating supersaturated air an ideal mixing model (saturated humid air and water droplets (or ice crystals) homogeneously mixed) is applied

Result for Wrong Input Values:

c_ptW_HAP_IP = -1000

References:

$c(p,t,W)$ Herrmann et al. [1], [2]

Isobaric Heat Capacity c_p = f(p,t,W)

Function Name:

cp_ptW_HAP_IP

Fortran Program:

REAL*8 FUNCTION CP_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in psi
t - Temperature t in °F
W - Humidity ratio W in $\mathrm{lb_w/lb_a}$

Result:

cp_ptW_HAP_IP - Isobaric heat capacity of humid air in Btu/(lb °R)

Range of Validity:

Temperature t:	from -225.67°F to 662°F
Total pressure p:	from 0.00145 psi to 1450.4 psi
Humidity ratio W:	$0 \le W \le W_\mathrm{s}$

Comments:

- Isobaric heat capacity $c_p = \left(\frac{\partial h}{\partial T}\right)_\mathrm{p}$
- Calculation for supersaturated humid air ($W > W_\mathrm{s}$) is not possible

Result for Wrong Input Values:

cp_ptW_HAP_IP = -1000

References:

$c_p(p,t,W)$ Herrmann et al. [1], [2]

Isochoric Heat Capacity c_v = f(p,t,W)

Function Name:

cv_ptW_HAP_IP

Fortran Program:

REAL*8 FUNCTION CV_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in psi
t - Temperature t in °F
W - Humidity ratio W in $\mathrm{lb_w/lb_a}$

Result:

cv_ptW_HAP_IP - Isochoric heat capacity of humid air in Btu/(lb °R)

Range of Validity:

Temperature t:	from -225.67°F to 662°F
Total pressure p:	from 0.00145 psi to 1450.4 psi
Humidity ratio W:	$0 \le W \le W_\mathrm{s}$

Comments:

- Isochoric heat capacity $c_v = \left(\frac{\partial u}{\partial T}\right)_\mathrm{v}$
- Calculation for supersaturated humid air ($W > W_\mathrm{s}$) is not possible

Result for Wrong Input Values:

cv_ptW_HAP_IP = -1000

References:

$c_v(p,t,W)$ Herrmann et al. [3], [4]

Enhancement Factor *f* = f(*p*,*t*)

Function Name:

f_pt_HAP_IP

Fortran Program:

REAL*8 FUNCTION   F_PT_HUAIRPROP(P,T), REAL*8 P,T

Input Values:

p	-	Total pressure p in psi
t	-	Temperature t in °F

Result:

f_pt_HAP_IP - Enhancement factor of water (decimal ratio)

Range of Validity:

Temperature t:	from -225.67°F to 662°F
Total pressure p:	from 0.00145 psi to 1450.4 psi

Comments:

- Enhancement factor $f = \frac{p_{\mathrm{H2O,s}}}{p_{\mathrm{s}}(t)}$

  with $p_{\mathrm{s}}(t)$ for $t \geq 32°\mathrm{F}$ - Steam pressure of water

  for $t < 32°\mathrm{F}$ - Sublimation pressure of water

- Describes the enhancement of the saturation pressure of water in the air atmosphere under elevated pressure
- Derived iteratively from the isothermal compressibility of liquid water, from Henry's constant [15], [16] and from the virial coefficients of air, water, and the air-water mixture

Result for Wrong Input Values:

f_pt_HAP_IP = -1000

References:

$f(p,t)$	Herrmann et al. [1], [2]

Air-Specific Enthalpy *h* = f(*p*,*t*,*W*)

Function Name:

h_ptW_HAP_IP

Fortran Program:

REAL*8 FUNCTION H_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in psi
t - Temperature t in °F
W - Humidity ratio W in $\mathrm{lb_w/lb_a}$

Result:

h_ptW_HAP_IP - Air-specific enthalpy in $\mathrm{Btu/lb_a}$

Range of Validity:

Temperature t:	from -225.67°F to 662°F
Total pressure p:	from 0.00145 psi to 1450.4 psi
Humidity ratio W:	$0 \le W \le 10\,\mathrm{lb_w/lb_a}$

Comments:

- When calculating supersaturated air an ideal mixing model (saturated humid air and water droplets (or ice crystals) homogeneously mixed) is applied

Result for Wrong Input Values:

h_ptW_HAP_IP = -1000

References:

$h(p,t,W)$	Herrmann et al. [1], [2]
$h_w(p,t)$	IAPWS-IF97 [7], [8] and IAPWS-06 [11]
$h_a(t)$	Lemmon et al. [14]

Dynamic Viscosity η = f(p,t,W)

Function Name:

Eta_ptW_HAP_IP

Fortran Program:

```
REAL*8 FUNCTION   ETA_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W
```

Input Values:

p - Total pressure p in psi
t - Temperature t in °F
W - Humidity ratio W in $\mathrm{lb_w/lb_a}$

Result:

Eta_ptW_HAP_IP - Dynamic viscosity of humid air in (lb s/ft²)

Range of Validity:

Temperature t:	from -99.67°F to 662°F
Total pressure p:	from 0.00145 psi to 1450.4 psi
Humidity ratio W:	$0 \le W \le 10\,\mathrm{lb_w/lb_a}$

Comments:

- A new very accurate algorithm is implemented between 32°F and 662°F
- When calculating supersaturated air an ideal mixing model (saturated humid air and water droplets (or ice crystals) homogeneously mixed) is applied

Result for Wrong Input Values:

Eta_ptW_HAP_IP = -1000

References:

$\eta(p,t,W)$	Herrmann et al. [3], [4]
$\eta_\mathrm{w}(p,t)$	IAPWS-IF97 [7], [8] and IAPWS-06 [19]
$\eta_\mathrm{a}(t)$	Lemmon et al. [18]

Isentropic Exponent $\kappa = f(p, t, W)$

Function Name:

Kappa_ptW_HAP_IP

Fortran Program:

REAL*8 FUNCTION KAPPA_PTW_HUAIRPROP(P,T, W), REAL*8 P,T,W

Input Values:

p - Total pressure p in psi
t - Temperature t in °F
W - Humidity ratio W in lb_w/lb_a

Result:

Kappa_ptW_HAP_IP - Isentropic exponent

Range of Validity:

Temperature t:	from -225.67°F to 662°F
Total pressure p:	from 0.00145 psi to 1450.4 psi
Humidity ratio W:	$0 \le W \le 10\,lb_w/lb_a$

Comments:

- Isentropic exponent $\kappa = -\frac{v}{p}\left(\frac{\partial p}{\partial v}\right)_s$
- When calculating supersaturated air an ideal mixing model (saturated humid air and water droplets homogeneously mixed) is applied for $t \geq 32$°F. For temperatures below (ice fog) the value of the saturated state is applied.

Result for Wrong Input Values:

Kappa_ptW_HAP_IP = -1000

References:

$v(p,t,W)$ Herrmann et al. [1], [2]

Thermal Conductivity $\lambda = f(p,t,W)$

Function Name:

Lambda_ptW_HAP_IP

Fortran Program:

```
REAL*8 FUNCTION   LAMBDA_PTW_HUAIRPROP(P,T, W), REAL*8 P,T,W
```

Input Values:

p - Total pressure p in psi
t - Temperature t in °F
W - Humidity ratio W in $\mathrm{lb_w/lb_a}$

Result:

Lambda_ptW_HAP_IP - Thermal conductivity in Btu/(h ft °R)

Range of Validity:

Temperature t:	from -99.67°F to 662°F
Total pressure p:	from 0.00145 psi to 1450.4 psi
Humidity ratio W:	$0 \le W \le 10\,\mathrm{lb_w/lb_a}$

Comments:

- A new very accurate algorithm is implemented between 32°F and 662°F
- When calculating supersaturated air an ideal mixing model (saturated humid air and water droplets (or ice crystals) homogeneously mixed) is applied

Result for Wrong Input Values:

Lambda_ptW_HAP_IP = -1000

References:

$\lambda(p,t,W)$	Herrmann et al. [3], [4]
$\lambda_w(p,t)$	IAPWS-IF97 [7], [8] and IAPWS-08 [20]
$\lambda_a(t)$	Lemmon et al. [18]

Kinematic Viscosity ν = f(p,t,W)

Function Name:

Ny_ptW_HAP_IP

Fortran Program:

REAL*8 FUNCTION   NY_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in psi
t - Temperature t in °F
W - Humidity ratio W in lb_w/lb_a

Result:

Ny_ptW_HAP_IP - Kinematic viscosity in ft^2/s

Range of Validity:

Temperature t:	from -99.67°F to 662°F
Total pressure p:	from 0.00145 psi to 1450.4 psi
Humidity ratio W:	$0 \le W \le W_s$

Comments:

- Kinematic Viscosity $\nu = \frac{\eta}{\rho}$

Result for Wrong Input Values:

Ny_ptW_HAP_IP = -1000

References:

$\eta(p,t,W)$	Herrmann et al. [3], [4]
$\rho(p,t,W)$	Herrmann et al. [1], [2]

Backward Function: Pressure p = f(t,s,W)

Function Name:

p_tsW_HAP_IP

Fortran Program:

REAL*8 FUNCTION   P_TSW_HUAIRPROP(T,S,W), REAL*8 T,S,W

Input Values:

t - Temperature t in °F

s - Air-specific entropy s in Btu/(lb$_a$ °R)

W - Humidity ratio W in lb$_w$/lb$_a$

Result:

p_tsW_HAP_IP - Total pressure of humid air in psi

Range of Validity:

Temperature t:	from -225.67°F to 662°F
Air-specific entropy s:	from -6.32 Btu/(lb$_a$ °R) to 9.32877 Btu/(lb$_a$ °R)
Humidity ratio W:	$0 \le W \le 10$ lb$_w$/lb$_a$

Comments:

- Iteration of total pressure p from s = f(p,t,W)

Result for Wrong Input Values:

p_tsW_HAP_IP = -1000

References:

$s(p,t,W)$ Herrmann et al. [1], [2]

Pressure p = f(z_{ele})

Function Name:

p_zele_HAP_IP

Fortran Program:

REAL*8 FUNCTION P_ZELE_HUAIRPROP(ZELE), REAL*8 ZELE

Input Values:

z_{ele} - Elevation z_{ele} in ft

Result:

p_zele_HAP_IP - Pressure of humid air in psi

Range of Validity:

Elevation z_{ele} from -16,404 ft to 36,089 ft

Comments:

- Pressure of humid air from elevation
- $p(z_{ele}) = 14.696\,\mathrm{psi} \cdot \left(1 - 6.8754 \cdot 10^{-6} \cdot \frac{z_{ele}}{\mathrm{ft}}\right)^{5.256}$

Result for Wrong Input Values:

p_zele_HAP_IP = -1000

References:

$p(z_{ele})$ ASHRAE [23]

Partial Pressure of Air p_{Air} = f(p,t,W)

Function Name:

pAir_ptW_HAP_IP

Fortran Program:

REAL*8 FUNCTION PAIR_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in psi
t - Temperature t in °F
W - Humidity ratio W in lb_w/lb_a

Result:

pAir_ptW_HAP_IP - Partial pressure of (dry) air in humid air in psi

Range of Validity:

Temperature t:	from -225.67°F to 662°F
Total pressure p:	from 0.00145 psi to 1450.4 psi
Humidity ratio W:	$0 \le W \le 10\,lb_w/lb_a$

Comments:

- Partial pressure of (dry) air in humid air $p_{Air} = 1 - p_{H2O}$
- Partial pressure of water vapor at saturation is calculated in case of supersaturated humid air ($W > W_s(p,t)$)
- The temperature value is used to calculate the saturation state

Result for Wrong Input Values:

pAir_ptW_HAP_IP = -1000

References:

$p_{H2O}(p,W)$ Herrmann et al. [1], [2]

Partial Pressure of Water Vapor p_{H2O} = f(p, t, W)

Function Name:

pH2O_ptW_HAP_IP

Fortran Program:

REAL*8 FUNCTION   PH2O_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in psi
t - Temperature t in °F
W - Humidity ratio W in $\mathrm{lb_w/lb_a}$

Result:

pH2O_ptW_HAP_IP - Partial pressure of water vapor in humid air in psi

Range of Validity:

Temperature t:	from -225.67°F to 662°F
Total pressure p:	from 0.00145 psi to 1450.4 psi
Humidity ratio W:	$0 \le W \le 10\,\mathrm{lb_w/lb_a}$

Comments:

- Partial pressure of water vapor in humid air $p_{H2O} = \dfrac{W \cdot p}{\left(\dfrac{R_a}{R_w} + W\right)}$
- Partial pressure of water vapor at saturation is calculated in case of supersaturated humid air ($W > W_s(p,t)$)
- The temperature value is used to calculate the saturation state

Result for Wrong Input Values:

pH2O_ptW_HAP_IP = -1000

References:

$p_{H2O}(p,W)$ Herrmann et al. [1], [2]

Partial Sat. Pressure of Water Vapor in Humid Air $p_{H2O,s}$ = f(p,t)

Function Name:

pH2Os_pt_HAP_IP

Fortran Program:

REAL*8 FUNCTION PH2OS_PT_HUAIRPROP(P,T), REAL*8 P,T

Input Values:

p - Total pressure *p* in psi

t - Temperature *t* in °F

Result:

pH2Os_pt_HAP_IP - Partial saturation pressure of water vapor in humid air in psi

Range of Validity:

Temperature *t*:	from -225.67°F to 662°F
Total pressure *p*:	from 0.00145 psi to 1450.4 psi

Comments:

- Partial pressure of water vapor at saturation $p_{H2O,s} = f \cdot p_s(t)$
with $p_s(t)$ for $t \geq 32$°F - Steam pressure of water
for $t < 32$°F - Sublimation pressure of water

Result for Wrong Input Values:

pH2Os_pt_HAP_IP = -1000

References:

$f(p,t)$		Herrmann et al. [1], [2]
$p_s(t)$	for $t \geq 32$°F	IAPWS-IF97 [7], [8]
	for $t < 32$°F	IAPWS-08 [11]

Relative Humidity φ = f(p,t,W)

Function Name:

phi_ptW_HAP_IP

Fortran Program:

REAL*8 FUNCTION PHI_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in psi
t - Temperature t in °F
W - Humidity ratio W in $\mathrm{lb_w/lb_a}$

Result:

phi_ptW_HAP_IP - Relative humidity (decimal ratio)

Range of Validity:

Temperature t:	from -225.67°F to 662°F
Total pressure p:	from 0.00145 psi to 1450.4 psi
Humidity ratio W:	$0 \le W \le 10\ \mathrm{lb_w/lb_a}$

Comments:

- Relative humidity $\varphi = \dfrac{p_{\mathrm{H2O}}}{p_{\mathrm{H2O,s}}}$
- This equation is valid for $p_{\mathrm{H2O}} \le p_{\mathrm{H2O,s}}$ and for $0 \le \varphi \le 1$

Result for Wrong Input Values:

phi_ptW_HAP_IP = -1000

References:

$\varphi(p,t,W)$ Herrmann et al. [1], [2]

Prandtl Number *Pr* = f(*p*,*t*,*W*)

Function Name:

Pr_ptW_HAP_IP

Fortran Program:

REAL*8 FUNCTION   PR_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in psi
t - Temperature t in °F
W - Humidity ratio W in $\mathrm{lb_w/lb_a}$

Result:

Pr_ptW_HAP_IP - Prandtl number

Range of Validity:

Temperature t:	from -99.67°F to 662°F
Total pressure p:	from 0.00145 psi to 1450.4 psi
Humidity ratio W:	$0 \le W \le 10\,\mathrm{lb_w/lb_a}$

Comments:

- Prandtl number $Pr = \frac{\eta \cdot c_p}{\lambda}$
- Calculation for supersaturated humid air ($W > W_s$) is not possible

Result for Wrong Input Values:

Pr_ptW_HAP_IP = -1000

References:

$\eta(p,t,W)$	Herrmann et al. [3], [4]
$c_p(p,t,W)$	Herrmann et al. [3], [4]
$\lambda(p,t,W)$	Lemmon et al. [20]

Mole Fraction of Air ψ_{Air} = f(W)

Function Name:

PsiAir_W_HAP_IP

Fortran Program:

REAL*8 FUNCTION PSIAIR_W_HUAIRPROP(W), REAL*8 W

Input Values:

W - Humidity ratio W in $\mathrm{lb_w/lb_a}$

Result:

PsiAir_W_HAP_IP - Mole fraction of (dry) air in humid air in $\mathrm{mol_a/mol}$

Range of Validity:

Humidity ratio W: $0 \le W \le 10\,\mathrm{lb_w/lb_a}$

Comments:

- Mole fraction of air $\psi_{\mathrm{Air}} = 1 - \psi_{\mathrm{H2O}} = 1 - \left(\dfrac{W}{\dfrac{R_{\mathrm{a}}}{R_{\mathrm{H2O}}} + W} \right)$

Result for Wrong Input Values:

PsiAir_W_HAP_IP = -1000

References:

$\psi_{\mathrm{Air}}(W)$ Herrmann et al. [1], [2]

Mole Fraction of Water ψ_{H2O} = f(W)

Function Name:

PsiH2O_W_HAP_IP

Fortran Program:

REAL*8 FUNCTION PSIH2O_W_HUAIRPROP(W), REAL*8 W

Input Values:

W - Humidity ratio W in $\mathrm{lb_w/lb_a}$

Result:

PsiH2O_W_HAP_IP - Mole fraction of water in humid air in $\mathrm{mol_w/mol}$

Range of Validity:

Humidity ratio W: $0 \le W \le 10\,\mathrm{lb_w/lb_a}$

Comments:

- Mole fraction of water $\psi_{\mathrm{H2O}} = \dfrac{W}{\dfrac{R_a}{\mathrm{R_{H2O}}} + W}$

Result for Wrong Input Values:

PsiH2O_W_HAP_IP = -1000

References:

$\psi_{\mathrm{H2O}}(W)$ Herrmann et al. [1], [2]

Density ρ = f(p,t,W)

Function Name:

Rho_ptW_HAP_IP

Fortran Program:

REAL*8 FUNCTION RHO_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in psi
t - Temperature t in °F
W - Humidity ratio W in $\mathrm{lb_w/lb_a}$

Result:

Rho_ptW_HAP_IP - Density of humid air in $\mathrm{lb/ft^3}$

Range of Validity:

Temperature t:	from -225.67°F to 662°F
Total pressure p:	from 0.00145 psi to 1450.4 psi
Humidity ratio W:	$0 \le W \le 10\,\mathrm{lb_w/lb_a}$

Comments:

- Density of humid air obtained from air-specific volume: $\rho = \dfrac{1+W}{v}$

Result for Wrong Input Values:

Rho_ptW_HAP_IP = -1000

References:

$\rho(p,t,W)$ Herrmann et al. [1], [2]

Air-Specific Entropy *s* = f(*p*,*t*,*W*)

Function Name:

s_ptW_HAP_IP

Fortran Program:

REAL*8 FUNCTION S_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in psi
t - Temperature t in °F
W - Humidity ratio W in $\mathrm{lb_w/lb_a}$

Result:

s_ptW_HAP_IP - Air-specific entropy in $\mathrm{Btu/(lb_a \cdot °R)}$

Range of Validity:

Temperature *t*:	from -225.67°F to 662°F
Total pressure *p*:	from 0.00145 psi to 1450.4 psi
Humidity ratio *W*:	$0 \le W \le 10\,\mathrm{lb_w/lb_a}$

Comments:

- When calculating supersaturated air an ideal mixing model (saturated humid air and water droplets (or ice crystals) homogeneously mixed) is applied

Result for Wrong Input Values:

s_ptW_HAP_IP = -1000

References:

$s(p,t,W)$ Herrmann et al. [1], [2]

Backward Function: Temperature *t* = f(*p*,*h*,*φ*)

Function Name:

t_phphi_HAP_IP

Fortran Program:

```
REAL*8 FUNCTION   T_PHPHI_HUAIRPROP(P,H,PHI), REAL*8 P,H,PHI
```

Input Values:

p	-	Total pressure p in psi
h	-	Air-specific enthalpy h in Btu/lb_a
φ	-	Relative humidity φ (decimal ratio)

Result:

t_phphi_HAP_IP - Temperature from pressure, enthalpy, and relative humidity in °F

Range of Validity:

Total pressure p:	from 0.00145 psi to 1450.4 psi
Air-specific enthalpy h:	from -2469.22 Btu/lb_a to 12772.088 Btu/lb_a
Relative humidity φ:	$0 \le \varphi \le 1$

Comments:

- Iteration of temperature t from $h = \text{f}(p,t,W)$ using $W = \text{f}(p,t,\varphi)$

Result for Wrong Input Values:

t_phphi_HAP_IP = -1000

References:

$h(p,t,W)$ Herrmann et al. [1], [2]

Backward Function: Temperature *t* = f(*p*,*h*,*W*)

Function Name:

t_phW_HAP_IP

Fortran Program:

REAL*8 FUNCTION T_PHW_HUAIRPROP(P,H,W), REAL*8 P,H,W

Input Values:

p - Total pressure *p* in psi
h - Air-specific enthalpy *h* in Btu/lb_a
W - Humidity ratio *W* in lb_w/lb_a

Result:

t_phW_HAP_IP - Temperature from pressure, enthalpy, and humidity ratio in °F

Range of Validity:

Total pressure *p*:	from 0.00145 psi to 1450.4 psi
Air-specific enthalpy *h*:	from -2469.22 Btu/lb_a to 12772.088 Btu/lb_a
Humidity ratio *W*:	$0 \le W \le 10\,\text{lb}_w/\text{lb}_a$

Comments:

- Iteration of temperature *t* from *h* = f(*p*,*t*,*W*)

Result for Wrong Input Values:

t_phW_HAP_IP = -1000

References:

$h(p,t,W)$ Herrmann et al. [1], [2]

Backward Function: Temperature *t* = f(*p*,*s*,*W*)

Function Name:

t_psW_HAP_IP

Fortran Program:

REAL*8 FUNCTION T_PSW_HUAIRPROP(P,S,W), REAL*8 P,S,W

Input Values:

p - Total pressure p in psi

s - Air-specific entropy in Btu/($\mathrm{lb_a} \cdot$ °R)

W - Humidity ratio W in $\mathrm{lb_w/lb_a}$

Result:

t_psW_HAP_IP - Temperature from pressure, entropy, and humidity ratio in °F

Range of Validity:

Total pressure p: from 0.00145 psi to 1450.4 psi

Air-specific entropy s: from -6.32 Btu/($\mathrm{lb_a}$ °R) to 9.32877 Btu/($\mathrm{lb_a}$ °R)

Humidity ratio W: $0 \le W \le 10\,\mathrm{lb_w/lb_a}$

Comments:

- Iteration of temperature t from s = f(p,t,W)

Result for Wrong Input Values:

t_psW_HAP_IP = -1000

References:

$s(p,t,W)$ Herrmann et al. [1], [2]

Backward Function: Temperature $t = f(p, t_{wb}, W)$

Function Name:

t_ptwbW_HAP_IP

Fortran Program:

REAL*8 FUNCTION   T_PTWBW_HUAIRPROP(P,TWB,W), REAL*8 P,TWB,W

Input Values:

p - Total pressure p in psi
t_{wb} - Wet-bulb temperature in °F
W - Humidity ratio W in lb_w/lb_a

Result:

t_ptwbW_HAP_IP - Temperature from pressure, wet bulb temperature and humidity ratio in °F

Range of Validity:

Total pressure p:	from 0.00145 psi to 1450.4 psi
Wet bulb temperature t_{wb}:	from -225.67°F to 662°F
Humidity ratio W:	$0 \le W \le 10\, lb_w/lb_a$

Comments:

- Iterationof temperature t from $t_{wb} = f(p, t, W)$

Result for Wrong Input Values:

t_ptwbW_HAP_IP = -1000

References:

$t_{wb}(p, t, W)$ Herrmann et al. [1], [2]

Dew-Point/Frost-Point Temperature t_d = f(p,W)

Function Name:

td_pW_HAP_IP

Fortran Program:

REAL*8 FUNCTION TD_PW_HUAIRPROP(P,W), REAL*8 P,W

Input Values:

p - Total pressure p in psi
W - Humidity ratio W in lb_w/lb_a

Result:

td_pW_HAP_IP - Dew-point/frost-point temperature in °F

Range of Validity:

Total pressure p:	from 0.00145 psi to 1450.4 psi
Humidity ratio W:	$0 \le W \le 10 \, lb_w/lb_a$

Comments:

Dew-point temperature $t_d = t_s(p_{H2O})$ for $t \ge 32°F$ (saturation temperature of water in humid air)

$t_d = t_{sub}(p_{H2O})$ for $t \le 32°F$ (sublimation temperature of water in humid air)

Result for Wrong Input Values:

td_pW_HAP_IP = -1000

References:

$t_s(p_{H2O})$	for $t_d \ge 32°F$	IAPWS-IF97 [7], [8]
$t_{sub}(p_{H2O})$	for $t_d \le 32°F$	IAPWS-08 [11]
p_{H2O}		Herrmann et. al. [1], [2]

Saturation Temperature t_s = f(p,p_{H2O})

Function Name:

ts_ppH2O_HAP_IP

Fortran Program:

REAL*8 FUNCTION TS_PPH2O_HUAIRPROP(P,PH2O), REAL*8 P,PH2O

Input Values:

p	- Total pressure p in psi
p_{H2O}	- Partial saturation pressure of water p_{H2O} in psi

Result:

ts_ppH2O_HAP_IP - Saturation temperature of water in humid air in °F

Range of Validity:

Total pressure p:	from 0.00145 psi to 1450.4 psi
Partial pressure p_{H2O} :	from 0.00145 psi to 1450.4 psi

Comments:

- Iteration of saturation temperature t_s from $p_{H2O,s} = f(p,t)$

Result for Wrong Input Values:

ts_ppH2O_HAP_IP = -1000

References:

$p_{H2O,s}$	Herrmann et. al. [1], [2]

Wet-Bulb/Ice-Bulb Temperature t_{wb} = f(p,t,W)

Function Name:

twb_ptW_HAP_IP

Fortran Program:

REAL*8 FUNCTION TWB_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in psi

t - Temperature t in °F

W - Humidity ratio W in $\mathrm{lb_w/lb_a}$

Result:

twb_ptW_HAP_IP - Wet-bulb/ice-bulb temperature in °F

Range of Validity:

Temperature t:	from -225.67°F to 662°F
Total pressure p:	from 0.00145 psi to 1450.4 psi
Humidity ratio W:	$0 \le W \le 10\,\mathrm{lb_w/lb_a}$

Comments:

- Iteration of wet-bulb temperature t_{wb} from $h^{\text{unsaturated}}(p,t,W) = h^{\text{fog}}(p,t_{wb},W)$
- Calculation for supersaturated humid air ($W > W_s$) is not possible

Result for Wrong Input Values:

twb_ptW_HAP_IP = -1000

References:

$t_{wb}(p,t,W)$ Herrmann et al. [1], [2]

Air-Specific Internal Energy *u* = f(*p*,*t*,*W*)

Function Name:

u_ptW_HAP_IP

Fortran Program:

REAL*8 FUNCTION   U_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in psi
t - Temperature t in °F
W - Humidity ratio W in $\text{lb}_\text{w}/\text{lb}_\text{a}$

Result:

u_ptW_HAP_IP - Air-specific internal energy in $\text{Btu}/\text{lb}_\text{a}$

Range of Validity:

Temperature t:	from -225.67°F to 662°F
Total pressure p:	from 0.00145 psi to 1450.4 psi
Humidity ratio W:	$0 \le W \le 10\,\text{lb}_\text{w}/\text{lb}_\text{a}$

Comments:

- Internal energy $u = h - pv$

Result for Wrong Input Values:

u_ptW_HAP_IP = -1000

References:

$u(p,t,W)$ Herrmann et al. [1], [2]

Air-Specific Volume *v* = f(*p*,*t*,*W*)

Function Name:

v_ptW_HAP_IP

Fortran Program:

REAL*8 FUNCTION V_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in psi

t - Temperature t in °F

W - Humidity ratio W in $\mathrm{lb_w/lb_a}$

Result:

v_ptW_HAP_IP - Air-specific volume in $\mathrm{ft^3/lb_a}$

Range of Validity:

Temperature t:	from -225.67°F to 662°F
Total pressure p:	from 0.00145 psi to 1450.4 psi
Humidity ratio W:	$0 \le W \le 10\ \mathrm{lb_w/lb_a}$

Comments:

- When calculating supersaturated air an ideal mixing model (saturated humid air and water droplets (or ice crystals) homogeneously mixed) is applied

Result for Wrong Input Values:

v_ptW_HAP_IP = -1000

References:

$v(p,t,W)$ Herrmann et al. [1], [2]

Humidity Ratio from Partial Pressure of Water Vapor $W = f(p,t,p_{H2O})$

Function Name:

W_ptpH2O_HAP_IP

Fortran Program:

REAL*8 FUNCTION W_PTPH2O_HUAIRPROP(P,T,PH2O), REAL*8 P,T,PH2O

Input Values:

p - Total pressure p in psi
t - Temperature t in °F
p_{H2O} - Partial pressure of water p_{H2O} in psi

Result:

W_ptpH2O_HAP_IP - Humidity ratio from pressure, temperature and partial pressure of water vapor in lb_w/lb_a

Range of Validity:

Total pressure p:	from 0.00145 psi to 1450.4 psi
Temperature t :	from -225.67°F to 662°F
Partial pressure p_{H2O}:	from 0.00145 psi to 1450.4 psi

Comments:

- Iteration of humidity ratio W from $p_{H2O} = f(p,t,W)$
- Result for supersaturated humid air is W_s

Result for Wrong Input Values:

W_ptpH2O_HAP_IP = -1000

References:

$p_{H2O}(p,t,W)$ Herrmann et al. [1], [2]

Humidity Ratio from Relative Humidity $W = f(p,t,\varphi)$

Function Name:

W_ptphi_HAP_IP

Fortran Program:

REAL*8 FUNCTION W_PTPHI_HUAIRPROP(P,T,PHI), REAL*8 P,T,PHI

Input Values:

p - Total pressure p in psi
t - Temperature t in °F
φ - Relative humidity (decimal ratio)

Result:

W_ptphi_HAP_IP - Humidity ratio from pressure, temperature and relative humidity in lb_w/lb_a

Range of Validity:

Temperature t:	from -225.67°F to 662°F
Total pressure p:	from 0.00145 psi to 1450.4 psi
Relative humidity φ:	$0 \le \varphi \le 1$

Comments:

- Iteration of humidity ratio W from $\varphi = f(p,t,W)$

Result for Wrong Input Values:

W_ptphi_HAP_IP = -1000

References:

$\varphi(p,t,W)$ Herrmann et al. [1], [2]

Humidity Ratio from Dew-Point Temperature $W = f(p,t_d)$

Function Name:

W_ptd_HAP_IP

Fortran Program:

REAL*8 FUNCTION W_PTD_HUAIRPROP(P,TD), REAL*8 P,TD

Input Values:

p - Total pressure p in psi

t_d - Dew-point temperature t_d in °F

Result:

W_ptd_HAP_IP - Humidity ratio from pressure and dew-point temperature in lb_w/lb_a

Range of Validity:

Dew point temperature t_d:	from -225.67°F to 662°F
Total pressure p:	from 0.00145 psi to 1450.4 psi

Comments:

- Iteration of humidity ratio W from $t_d = f(p,W)$

Result for Wrong Input Values:

W_ptd_HAP_IP = -1000

References:

$t_d(p,W)$ Herrmann et al. [1], [2]

Humidity Ratio from Wet-Bulb Temperature $W = f(p,t,t_{wb})$

Function Name:

W_pttwb_HAP_IP

Fortran Program:

REAL*8 FUNCTION W_PTTWB_HUAIRPROP(P,T,TWB), REAL*8 P,T,TWB

Input Values:

p - Total pressure p in psi
t - Temperature t in °F
t_{wb} - Wet-bulb temperature in °F

Result:

W_pttwb_HAP_IP - Humidity ratio from pressure, temperature and wet-bulb temperature in lb_w/lb_a

Range of Validity:

Total pressure p:	from 0.00145 psi to 1450.4 psi
Temperature t:	from -225.67°F to 662°F
Wet-bulb temperature t_{wb}:	from -225.67°F to 662°F

Comments:

- Iteration of humidity ratio W from $t_{wb} = f(p,t,W)$
- Calculation for supersaturated humid air ($W > W_s$) is not possible

Result for Wrong Input Values:

W_pttwb_HAP_IP = -1000

References:

$t_{wb}(p,t,W)$ Herrmann et al. [1], [2]

Saturation Humidity Ratio W_s = f(p,t)

Function Name:

Ws_pt_HAP_IP

Fortran Program:

REAL*8 FUNCTION WS_PT_HUAIRPROP(P,T), REAL*8 P,T

Input Values:

p - Total pressure *p* in psi
t - Temperature *t* in °F

Result:

Ws_pt_HAP_IP - Saturation humidity ratio in lb_w/lb_a

Range of Validity:

Total pressure *p*: from 0.00145 psi to 1450.4 psi
Temperature *t*: from -225.67°F to 662°F

Comments:

- Calculation of saturation humidity ratio W_s from $W_s = \frac{M_{H2O}}{M_a} \frac{p_{H2O,s}}{\left(p - p_{H2O,s}\right)}$

Result for Wrong Input Values:

Ws_pt_HAP_IP = -1000

References:

$p_{H2O,s}$ Herrmann et al. [1], [2]

Mass Fraction of Air ξ_{Air} = f(W)

Function Name:

XiAir_W_HAP_IP

Fortran Program:

REAL*8 FUNCTION   XIAIR_W_HUAIRPROP(W), REAL*8 W

Input Values:

W - Humidity ratio W in $\mathrm{lb_w/lb_a}$

Result:

XiAir_W_HAP_IP - Mass fraction of (dry) air in humid air in $\mathrm{lb_a/lb}$

Range of Validity:

Humidity ratio W: $0 \leq W \leq 10\,\mathrm{lb_w/lb_a}$

Comments:

- Mass fraction of (dry) air $\xi_{Air} = 1 - \xi_{H2O} = 1 - \dfrac{W}{1+W}$

Result for Wrong Input Values:

XiAir_W_HAP_IP = -1000

References:

$\xi_{Air}(W)$ Herrmann et al. [1], [2]

Mass Fraction of Water Vapor in Humid Air ξ_{H2O} = f(W)

Function Name:

XiH2O_W_HAP_IP

Fortran Program:

REAL*8 FUNCTION XIH2O_W_HUAIRPROP(W), REAL*8 W

Input Values:

W - Humidity ratio W in lb_w/lb_a

Result:

XiH2O_W_HAP_IP - Mass fraction of water vapor in humid air in lb_w/lb

Range of Validity:

Humidity ratio W: $0 \le W \le 10\,lb_w/lb_a$

Comments:

- Mass fraction of water $\xi_{H2O} = \dfrac{W}{1+W}$

Result for Wrong Input Values:

XiH2O_W_HAP_IP = -1000

References:

$\xi_{H2O}(W)$ Herrmann et al. [1], [2]

Compression Factor $Z = \mathrm{f}(p,t,W)$

Function Name:

Z_ptW_HAP_IP

Fortran Program:

REAL*8 FUNCTION   Z_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in psi
t - Temperature t in °F
W - Humidity ratio W in $\mathrm{lb_w/lb_a}$

Result:

Z_ptW_HAP_IP - Compression factor (decimal ratio)

Range of Validity:

Total pressure p:	from 0.00145 psi to 1450.4 psi
Temperature t:	from -225.67°F to 662°F
Humidity ratio W:	$0 \le W \le W_s$

Comments:

- Compression factor $Z = 1 + \dfrac{B_m}{\bar{v}} + \dfrac{C_m}{\bar{v}^2}$

  with $\bar{v} = \dfrac{M}{\rho} = \dfrac{Mv}{1+W}$

  and M is the molar mass of humid air

- Calculation for supersaturated humid air ($W > W_s$) is not possible

Result for Wrong Input Values:

Z_ptW_HAP_IP = -1000

References:

$B_m(t,W), C_m(t,W)$	Herrmann et al. [1], [2]
$\rho(p,t,W), v(p,t,W)$	Herrmann et al. [1], [2]

3.2 Functions for Steam and Water for Temperatures $t \geq 32°F$

Specific Enthalpy of Liquid Water $h_{\text{liq}} = \text{f}(p,t)$

Function Name:

hliq_pt_97_IP

Fortran Program:

REAL*8 FUNCTION   HLIQ_PT_97(P,T), REAL*8 P,T

Input Values:

p	-	Pressure *p* in psi
t	-	Temperature *t* in °F

Result:

hliq_pt_97_IP - Specific enthalpy of liquid water in Btu/lb

Range of Validity:

Pressure *p*:	from $p_s(32°\text{F}) = 0.08865$ psi to 1450.4 psi
Temperature *t*:	from 32°F to 662°F

Comments:

- Specific enthalpy of liquid water $h_{\text{liq}} = h^{97}(p,t)$ (Region 1)

Result for Wrong Input Values:

hliq_pt_97_IP = -1000

References:

$h^{97}(p,t)$ IAPWS-IF97 [7], [8]

Specific Enthalpy of Saturated Liquid Water $h_{\mathrm{liq,s}} = \mathrm{f}(t)$

Function Name:

hliqs_t_97_IP

Fortran Program:

REAL*8 FUNCTION HLIQS_T_97(T), REAL*8 T

Input Values:

t - Temperature *t* in °F

Result:

hliqs_t_97_IP - Specific enthalpy of saturated liquid water in Btu/lb

Range of Validity:

Temperature *t*: from 32°F to 662°F

Comments:

- Specific enthalpy of liquid water $h_{\mathrm{liq,s}} = h^{97}(p_{\mathrm{s}}, t)$ (Region 1) with $p_{\mathrm{s}} = p_{\mathrm{s}}^{97}(t)$

Result for Wrong Input Values:

hliqs_t_97_IP = -1000

References:

$h^{97}(p,t)$, $p_{\mathrm{s}}^{97}(t)$ IAPWS-IF97 [7], [8]

Specific Enthalpy of Saturated Water Vapor $h_{\text{vap,s}} = f(t)$

Function Name:

hvaps_t_97_IP

Fortran Program:

REAL*8 FUNCTION HVAPS_T_97(T), REAL*8 T

Input Values:

t - Temperature *t* in °F

Result:

hvaps_t_97_IP - Specific enthalpy of saturated water vapor in Btu/lb

Range of Validity:

Temperature *t*:	from 32°F to 662°F

Comments:

- Specific enthalpy of saturated water vapor $h_{\text{vap,s}} = h^{97}(p_{\text{s}}, t)$ (Region 2)
  with $p_{\text{s}} = p_{\text{s}}^{97}(t)$

Result for Wrong Input Values:

hvaps_t_97_IP = -1000

References:

$h^{97}(p,t)$, $p_{\text{s}}^{97}(t)$ IAPWS-IF97 [7], [8]

Saturation Pressure of Water p_s = f(t)

Function Name:

ps_t_97_IP

Fortran Program:

```
REAL*8 FUNCTION   PS_T_97(T), REAL*8 T
```

Input Values:

t - Temperature *t* in °F

Result:

ps_t_97_IP - Saturation pressure of water in psi

Range of Validity:

Temperature *t*: from 32°F to 662°F

Comments:

- Saturation pressure of water $p_s = p_s^{97}(t)$ (Region 4)

Result for Wrong Input Values:

ps_t_97_IP -1000

References:

$p_s^{97}(t)$ IAPWS-IF97 [7], [8]

Specific Entropy of Liquid Water $s_{\text{liq}} = \mathrm{f}(p, t)$

Function Name:

sliq_pt_97_IP

Fortran Program:

```
REAL*8 FUNCTION   SLIQ_PT_97(P,T), REAL*8 P,T
```

Input Values:

p	-	Pressure *p* in psi
t	-	Temperature *t* in °F

Result:

sliq_pt_97_IP - Specific entropy of liquid water in Btu/(lb °R)

Range of Validity:

Pressure *p*:	from $p_s(32°\text{F}) = 0.08865$ psi to 1450.4 psi
Temperature *t*:	from 32°F to 662°F

Comments:

- Specific entropy of liquid water $s_{\text{liq}} = s^{97}(p, t)$ (Region 1)

Result for Wrong Input Values:

sliq_pt_97_IP = -1000

References:

$s^{97}(p, t)$ IAPWS-IF97 [7], [8]

Specific Entropy of Saturated Liquid Water $s_{\mathrm{liq,s}}$ = f(t)

Function Name:

sliqs_t_97_IP

Fortran Program:

REAL*8 FUNCTION SLIQS_T_97(T), REAL*8 T

Input Values:

t - Temperature t in °F

Result:

sliqs_t_97_IP - Specific entropy of saturated liquid water in Btu/(lb °R)

Range of Validity:

Temperature t: from 32°F to 662°F

Comments:

- Specific entropy of liquid water $s_{\mathrm{liq,s}} = s^{97}(p_{\mathrm{s}}, t)$ (Region 1)
  with $p_{\mathrm{s}} = p_{\mathrm{s}}^{97}(t)$

Result for Wrong Input Values:

sliqs_t_97_IP = -1000

References:

$s^{97}(p,t)$, $p_{\mathrm{s}}^{97}(t)$ IAPWS-IF97 [7], [8]

Specific Entropy of Saturated Water Vapor $s_{\mathrm{vap,s}} = \mathrm{f}(t)$

Function Name:

svaps_t_97_IP

Fortran Program:

```
REAL*8 FUNCTION   SVAPS_T_97(T), REAL*8 T
```

Input Values:

t - Temperature *t* in °F

Result:

svaps_t_97_IP - Specific entropy of saturated water vapor in Btu/(lb °R)

Range of Validity:

Temperature *t*: from 32°F to 662°F

Comments:

- Specific entropy of saturated water vapor $s_{\mathrm{vap,s}} = s^{97}(p_\mathrm{s}, t)$ (Region 2) with $p_\mathrm{s} = p_\mathrm{s}^{97}(t)$

Result for Wrong Input Values:

svaps_t_97_IP = -1000

References:

$s^{97}(p,t)$, $p_\mathrm{s}^{97}(t)$ IAPWS-IF97 [7], [8]

Saturation Temperature of Water t_s = f(p)

Function Name:

ts_p_97_IP

Fortran Program:

REAL*8 FUNCTION   TS_P_97(P), REAL*8 P

Input Values:

p   -   Pressure *p* in psi

Result:

ts_p_97_IP - Saturation temperature of water in °F

Range of Validity:

Pressure *p*:   from 0.08865 psi to 1450.4 psi

Comments:

- Saturation temperature of water $t_s = t_s^{97}(p)$ (Region 4)

Result for Wrong Input Values:

ts_p_97_IP = -1000

References:

$t_s^{97}(p)$ IAPWS-IF97 [7], [8]

Specific Volume of Liquid Water $v_{\text{liq}} = \mathrm{f}(p, t)$

Function Name:

vliq_pt_97_IP

Fortran Program:

REAL*8 FUNCTION VLIQ_PT_97(P,T), REAL*8 P,T

Input Values:

p	-	Pressure p in psi
t	-	Temperature t in °F

Result:

vliq_pt_97_IP - Specific volume of liquid water in $\mathrm{ft}^3/\mathrm{lb}$

Range of Validity:

Pressure p:	from $p_\mathrm{s}(32°\mathrm{F}) = 0.08865$ psi to 1450.4 psi
Temperature t:	from 32°F to 662°F

Comments:

- Specific volume of liquid water $v_{\text{liq}} = v^{97}(p, t)$ (Region 1)

Result for Wrong Input Values:

vliq_pt_97_IP = -1000

References:

$v^{97}(p, t)$	IAPWS-IF97 [7], [8]

Specific Volume of Saturated Liquid Water $v_{\mathrm{liq,s}} = \mathrm{f}(t)$

Function Name:

vliqs_t_97_IP

Fortran Program:

REAL*8 FUNCTION   VLIQS_T_97(T), REAL*8 T

Input Values:

t   -   Temperature *t* in °F

Result:

vliqs_t_97_IP - Specific volume of saturated liquid water in $\mathrm{ft}^3/\mathrm{lb}$

Range of Validity:

Temperature *t*:   from 32°F to 662°F

Comments:

- Specific volume of liquid water $v_{\mathrm{liq,s}} = v^{97}(p_{\mathrm{s}}, t)$ (Region 1)

  with $p_{\mathrm{s}} = p_{\mathrm{s}}^{97}(t)$

Result for Wrong Input Values:

vliqs_t_97_IP = -1000

References:

$v^{97}(p,t)$, $p_{\mathrm{s}}^{97}(t)$ IAPWS-IF97 [7], [8]

Specific Volume of Saturated Water Vapor $v_{\mathrm{vap,s}} = \mathrm{f}(t)$

Function Name:

vvaps_t_97_IP

Fortran Program:

REAL*8 FUNCTION VVAPS_T_97(T), REAL*8 T

Input Values:

t - Temperature *t* in °F

Result:

vvaps_t_97_IP - Specific volume of saturated water vapor in ft^3/lb

Range of Validity:

Temperature *t*: from 32°F to 662°F

Comments:

- Specific volume of saturated water vapor $v_{\mathrm{vap,s}} = v^{97}(p_{\mathrm{s}},t)$ (Region 2)
  with $p_{\mathrm{s}} = p_{\mathrm{s}}^{97}(t)$

Result for Wrong Input Values:

vvaps_t_97_IP = -1000

References:

$v^{97}(p,t)$, $p_{\mathrm{s}}^{97}(t)$ IAPWS-IF97 [7], [8]

3.3 Functions for Steam and Ice for Temperatures *t* ≤ 32°F

Specific Enthalpy of Saturated Ice $h_{\mathrm{ice,sub}} = f(t)$

Function Name:

hicesub_t_06_IP

Fortran Program:

REAL*8 FUNCTION   HICESUB_T_06(T), REAL*8 T

Input Values:

t - Temperature *t* in °F

Result:

hicesub_t_06_IP - Specific enthalpy of saturated ice in Btu/lb

Range of Validity:

Temperature *t*: from -225.67°F to 32°F

Comments:

- Specific enthalpy of saturated ice $h_{\mathrm{ice,sub}} = h^{06}(p_{\mathrm{sub}}, t)$
  with $p_{\mathrm{sub}} = p_{\mathrm{sub}}^{08}(t)$

Result for Wrong Input Values:

hicesub_t_06_IP = -1000

References:

$h^{06}(p,t)$	IAPWS-06 [10]
$p_{\mathrm{sub}}^{08}(t)$	IAPWS-08 [11]

Specific Enthalpy of Saturated Water Vapor $h_{\mathrm{vap,sub}} = \mathrm{f}(t)$

Function Name:

hvapsub_t_95_IP

Fortran Program:

REAL*8 FUNCTION HVAPSUB_T_95(T), REAL*8 T

Input Values:

t - Temperature *t* in °F

Result:

hvapsub_t_95_IP - Specific enthalpy of saturated water vapor in Btu/lb

Range of Validity:

Temperature *t*: from -225.67°F to 32°F

Comments:

- Specific enthalpy of saturated water vapor $h_{\mathrm{vap,sub}} = h^{95}(p_{\mathrm{sub}}, t)$

  with $p_{\mathrm{sub}} = p_{\mathrm{sub}}^{08}(t)$

Result for Wrong Input Values:

hvapsub_t_95_IP = -1000

References:

$h^{95}(p,t)$	IAPWS-95 [5], [6]
$p_{\mathrm{sub}}^{08}(t)$	IAPWS-08 [11]

Melting Pressure of Ice $p_{\mathrm{mel}} = \mathrm{f}(t)$

Function Name:

pmel_t_08_IP

Fortran Program:

```
REAL*8 FUNCTION   PMEL_T_08 (T), REAL*8 T
```

Input Values:

t - Temperature t in °F

Result:

pmel_t_08_IP - Melting pressure of ice in psi

Range of Validity:

Temperature t: from -7.573°F to 32°F

Result for Wrong Input Values:

pmel_t_08_IP = -1000

References:

$p_{\mathrm{mel}}^{08}(t)$ IAPWS-08 [11]

Sublimation Pressure of Ice $p_{\text{sub}} = \text{f}(t)$

Function Name:

psub_t_08_IP

Fortran Program:

REAL*8 FUNCTION PSUB_T_08 (T), REAL*8 T

Input Values:

t - Temperature *t* in °F

Result:

psub_t_08_IP - Sublimation pressure of ice in psi

Range of Validity:

Temperature *t*: from -225.67°F to 32°F

Result for Wrong Input Values:

psub_t_08_IP = -1000

References:

$p_{\text{sub}}^{08}(t)$ IAPWS-08 [11]

Specific Entropy of Saturated Ice $s_{\text{ice,sub}}$ = f(t)

Function Name:

sicesub_t_06_IP

Fortran Program:

REAL*8 FUNCTION SICESUB_T_06(T), REAL*8 T

Input Values:

t - Temperature *t* in °F

Result:

sicesub_t_06_IP - Specific entropy of saturated ice in Btu/(lb °R)

Range of Validity:

Temperature *t*: from -225.67°F to 32°F

Comments:

- Specific entropy of saturated ice $s_{\text{ice,sub}} = s^{06}(p_{\text{sub}}, t)$
  with $p_{\text{sub}} = p_{\text{sub}}^{08}(t)$

Result for Wrong Input Values:

sicesub_t_06_IP = -1000

References:

$s^{06}(p,t)$ IAPWS-06 [10]

$p_{\text{sub}}^{08}(t)$ IAPWS-08 [11]

Specific Entropy of Saturated Water Vapor $s_{\mathrm{vap,sub}} = \mathrm{f}(t)$

Function Name:

svapsub_t_95_IP

Fortran Program:

REAL*8 FUNCTION SVAPSUB_T_95(T), REAL*8 T

Input Values:

t - Temperature *t* in °F

Result:

svapsub_t_95_IP - Specific entropy of saturated water vapor in Btu/(lb °R)

Range of Validity:

Temperature *t*: from -225.67°F to 32°F

Comments:

- Specific entropy of saturated water vapor $s_{\mathrm{vap,sub}} = s^{95}(p_{\mathrm{sub}}, t)$
  with $p_{\mathrm{sub}} = p_{\mathrm{sub}}^{08}(t)$

Result for Wrong Input Values:

svapsub_t_95_IP = -1000

References:

$s^{95}(p,t)$	IAPWS-95 [7], [8]
$p_{\mathrm{sub}}^{08}(t)$	IAPWS-08 [11]

Melting Temperature of Ice $t_{mel} = f(p)$

Function Name:

tmel_p_08_IP

Fortran Program:

```
REAL*8 FUNCTION   TMEL_P_08(P), REAL*8 P
```

Input Values:

p - Pressure p in psi

Result:

tmel_p_08_IP - Melting temperature of ice in °F

Range of Validity:

Pressure p: from $p_s(32°F) = 0.08865$ psi to 1450.4 psi

Result for Wrong Input Values:

tmel_p_08_IP = -1000

References:

$t_{mel}^{08}(p)$ IAPWS-08 [11]

Sublimation Temperature of Ice t_{sub} = f(p)

Function Name:

tsub_p_08_IP

Fortran Program:

```
REAL*8 FUNCTION   TSUB_P_08(P), REAL*8 P
```

Input Values:

p - Pressure *p* in psi

Result:

tsub_p_08_IP - Sublimation temperature of ice in °F

Range of Validity:

Pressure *p*: from $p_{subl}(-225.67°F) = 1.7407 \times 10^{-12}$ psi to $p_{subl}(32°F) = 0.08865$ psi

Result for Wrong Input Values:

tsub_p_08_IP = -1000

References:

$t_{sub}^{08}(p)$ IAPWS-08 [11]

Specific Volume of Saturated Ice $v_{\mathrm{ice,sub}} = \mathrm{f}(t)$

Function Name:

vicesub_t_06_IP

Fortran Program:

REAL*8 FUNCTION VICESUB_T_06(T), REAL*8 T

Input Values:

t - Temperature *t* in °F

Result:

vicesub_t_06_IP - Specific volume of saturated ice in $\mathrm{ft}^3/\mathrm{lb}$

Range of Validity:

Temperature *t*: from -225.67°F to 32°F

Comments:

- Specific volume of saturated ice $v_{\mathrm{ice,sub}} = v^{06}(p_{\mathrm{sub}}, t)$
  with $p_{\mathrm{sub}} = p_{\mathrm{sub}}^{08}(t)$

Result for Wrong Input Values:

vicesub_t_06_IP = -1000

References:

$v^{06}(p,t)$	IAPWS-06 [10]
$p_{\mathrm{sub}}^{08}(t)$	IAPWS-08 [11]

Specific Volume of Saturated Water Vapor $v_{\mathbf{vap,sub}}$ = f(t)

Function Name:

vvapsub_t_95_IP

Fortran Program:

```
REAL*8 FUNCTION   VVAPSUB_T_95(T), REAL*8 T
```

Input Values:

t - Temperature t in °F

Result:

vvapsub_t_95_IP - Specific volume of saturated water vapor in ft^3/lb

Range of Validity:

Temperature t: from -225.67°F to 32°F

Comments:

- Specific volume of saturated water vapor $v_{\text{vap,sub}} = v^{95}(p_{\text{sub}}, t)$

  with $p_{\text{sub}} = p_{\text{sub}}^{08}(t)$

Result for Wrong Input Values:

vvapsub_t_95_IP = -1000

References:

$v^{95}(p,t)$	IAPWS-95 [7], [8]
$p_{\text{sub}}^{08}(t)$	IAPWS-08 [11]

KCE ThermoFluidProperties

KCE-ThermoFluidProperties
www.thermofluidprop.com

Hochschule Zittau/Görlitz
UNIVERSITY OF APPLIED SCIENCES

4. Property Libraries for Calculating Heat Cycles, Boilers, Turbines and Refrigerators

Water and Steam

Library LibIF97

- Industrial Formulation IAPWS-IF97 (Revision 2007)
- Supplementary Standards IAPWS-IF97-S01, -S03rev, -S04, and -S05
- IAPWS Revised Advisory Note No. 3 on Thermodynamic Derivatives (2008)

Library LibIF97_META

- Industrial Formulation IAPWS-IF97 (Revision 2007) for metastable steam

Humid Combustion Gas Mixtures

Library LibHuGas

Model: Ideal mixture of the real fluids:

CO_2 - Span, Wagner H_2O - IAPWS-95
O_2 - Schmidt, Wagner N_2 - Span et al.
Ar - Tegeler et al.

and of the ideal gases:

SO_2, CO, Ne
(Scientific Formulation of Bücker et al.)

Consideration of:

- Dissociation from VDI 4670
- Poynting effect

Humid Air

Library LibHuAir

Model: Ideal mixture of the real fluids:

- Dry air from Lemmon et al.
- Steam, water and ice from IAPWS-IF97 and IAPWS-06

Consideration of:

- Condensation and freezing of steam
- Dissociation from VDI 4670
- Poynting effect from ASHRAE RP-1485

Extremely Fast Property Calculations

Spline-Based Table Look-up Method (SBTL)

Library LibSBTL_IF97
Library LibSBTL_95
Library LibSBTL_HuAir

For steam, water, humid air, carbon dioxide and other fluids and mixtures according IAPWS Guideline 2015 for Computational Fluid Dynamics (CFD), real-time and non-stationary simulations

Carbon Dioxide Including Dry Ice

Library LibCO2

Formulation of Span and Wagner (1996)

Seawater

Library LibSeaWa

IAPWS Industrial Formulation 2013

Ice

Library LibICE

Ice from IAPWS-06, Melting and sublimation pressures from IAPWS-08, Water from IAPWS-IF97, Steam from IAPWS-95 and -IF97

Ideal Gas Mixtures

Library LibIdGasMix

Model: Ideal mixture of the ideal gases:

Ar
Ne
N_2
O_2
CO
CO_2
Air
NO
H_2O
SO_2
H_2
H_2S
OH
He
F_2
NH_3
Methane
Ethane
Ethylene
Propylene
Propane
Iso-Butane
n-Butane
Benzene
Methanol

Consideration of:

- Dissociation from the VDI Guideline 4670

Library LibIDGAS

Model: Ideal gas mixture from VDI Guideline 4670

Consideration of:

- Dissociation from the VDI Guideline 4670

Humid Air

Library ASHRAE LibHuAirProp

Model: Virial equation from ASHRAE Report RP-1485 for real mixture of the real fluids:
- Dry air
- Steam

Consideration of:

- Enhancement of the partial saturation pressure of water vapor at elevated total pressures

www.ashrae.org/bookstore

Dry Air Including Liquid Air

Library LibRealAir

Formulation of Lemmon et al. (2000)

Refrigerants

Ammonia

Library LibNH3

Formulation of Tillner-Roth et al. (1993)

R134a

Library LibR134a

Formulation of Tillner-Roth and Baehr (1994)

Iso-Butane

Library LibButane_Iso

Formulation of Bücker and Wagner (2006)

n-Butane

Library LibButane_n

Formulation of Bücker and Wagner (2006)

Mixtures for Absorption Processes

Ammonia/Water Mixtures

Library LibAmWa

IAPWS Guideline 2001 of Tillner-Roth and Friend (1998)

Helmholtz energy equation for the mixing term

(also useable for calculating the Kalina Cycle)

Water/Lithium Bromide Mixtures

Library LibWaLi

Formulation of Kim and Infante Ferreira (2004)

Gibbs energy equation for the mixing term

Liquid Coolants

Liquid Secondary Refrigerants

Library LibSecRef

Liquid solutions of water with

$C_2H_6O_2$	Ethylene glycol
$C_3H_8O_2$	Propylene glycol
C_2H_5OH	Ethanol
CH_3OH	Methanol
$C_3H_8O_3$	Glycerol
K_2CO_3	Potassium carbonate
$CaCl_2$	Calcium chloride
$MgCl_2$	Magnesium chloride
NaCl	Sodium chloride
$C_2H_3KO_2$	Potassium acetate
$CHKO_2$	Potassium formate
LiCl	Lithium chloride
NH_3	Ammonia

Formulation of the International Institute of Refrigeration (IIR 2010)

Ethanol

Library LibC2H5OH

Formulation of
Schroeder et al. (2014)

Methanol

Library LibCH3OH

Formulation of
de Reuck and Craven (1993)

Propane

Library LibPropane

Formulation of
Lemmon et al. (2009)

Siloxanes as ORC Working Fluids

Octamethylcyclotetrasiloxane	$C_8H_{24}O_4Si_4$	**Library LibD4**
Decamethylcyclopentasiloxane	$C_{10}H_{30}O_5Si_5$	**Library LibD5**
Tetradecamethylhexasiloxane	$C_{14}H_{42}O_5Si_6$	**Library LibMD4M**
Hexamethyldisiloxane	$C_6H_{18}OSi_2$	**Library LibMM**

Formulation of Colonna et al. (2006)

Dodecamethylcyclohexasiloxane	$C_{12}H_{36}O_6Si_6$	**Library LibD6**
Decamethyltetrasiloxane	$C_{10}H_{30}O_3Si_4$	**Library LibMD2M**
Dodecamethylpentasiloxane	$C_{12}H_{36}O_4Si_5$	**Library LibMD3M**
Octamethyltrisiloxane	$C_8H_{24}O_2Si_3$	**Library LibMDM**

Formulation of Colonna et al. (2008)

Nitrogen and Oxygen

Libraries
LibN2 and LibO2

Formulations of Span et al. (2000)
and Schmidt and Wagner (1985)

Hydrogen

Library LibH2

Formulation of
Leachman et al. (2009)

Helium

Library LibHe

Formulation of
Arp et al. (1998)

Hydrocarbons

Decane	$C_{10}H_{22}$	**Library LibC10H22**
Isopentane	C_5H_{12}	**Library LibC5H12_Iso**
Neopentane	C_5H_{12}	**Library LibC5H12_Neo**
Isohexane	C_6H_{14}	**Library LibC6H14**
Toluene	C_7H_8	**Library LibC7H8**

Formulation of Lemmon and Span (2006)

Further Fluids

Carbon monoxide	CO	**Library LibCO**
Carbonyl sulfide	COS	**Library LibCOS**
Hydrogen sulfide	H_2S	**Library LibH2S**
Nitrous oxide	N_2O	**Library LibN2O**
Sulfur dioxide	SO_2	**Library LibSO2**
Acetone	C_3H_6O	**Library LibC3H6O**

Formulation of Lemmon and Span (2006)

KCE
ThermoFluidProperties

For more information please contact:

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Email: info@thermofluidprop.com
Phone: +49-9621-1762047
Mobile: +49-172-7914607
Fax: +49-3222-1095810

The following thermodynamic and transport properties can be calculated[a]:

Thermodynamic Properties

- Vapor pressure p_s
- Saturation temperature T_s
- Density ρ
- Specific volume v
- Enthalpy h
- Internal energy u
- Entropy s
- Exergy e
- Isobaric heat capacity c_p
- Isochoric heat capacity c_v
- Isentropic exponent κ
- Speed of sound w
- Surface tension σ

Transport Properties

- Dynamic viscosity η
- Kinematic viscosity ν
- Thermal conductivity λ
- Prandtl number Pr
- Thermal diffusivity a

Backward Functions

- T, v, s (p,h)
- T, v, h (p,s)
- p, T, v (h,s)
- p, T (v,h)
- p, T (v,u)

Thermodynamic Derivatives

- Partial derivatives used in process modeling can be calculated.

---

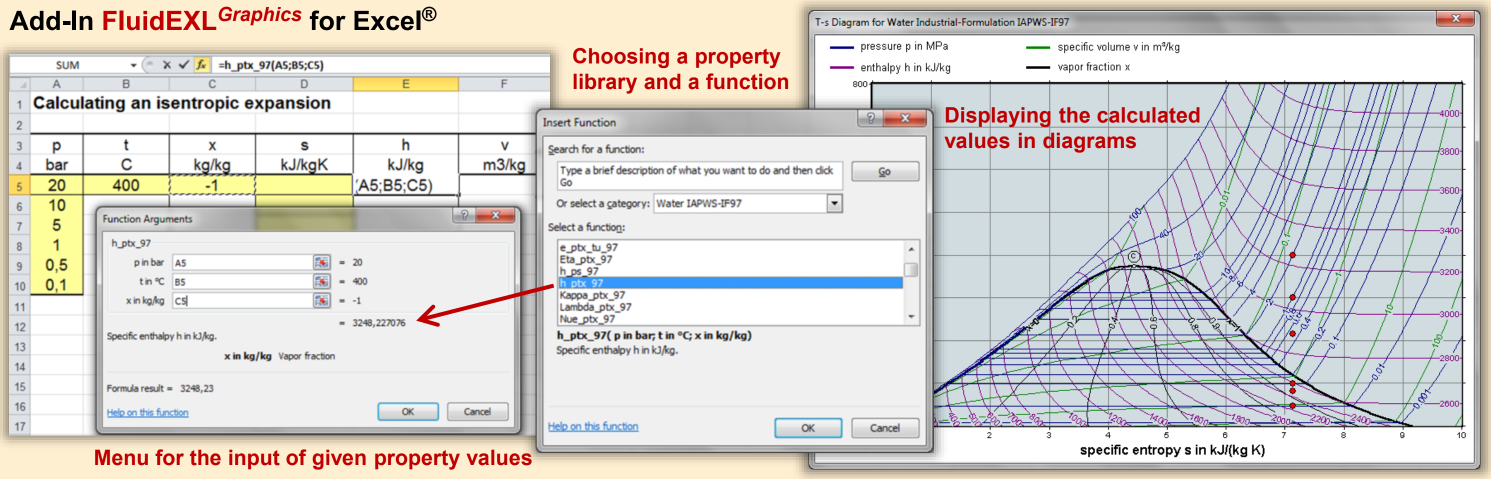
[a] Not all of these property functions are available in all property libraries.

www.thermofluidprop.com

KCE-ThermoFluidProperties
www.thermofluidprop.com

Property Software for Calculating Heat Cycles, Boilers, Turbines and Refrigerators

Add-In FluidEXL*Graphics* for Excel®



Choosing a property library and a function

Displaying the calculated values in diagrams

Menu for the input of given property values

=h_ptx_97(A5;B5;C5)

Calculating an isentropic expansion

p	t	x	s	h	v
bar	C	kg/kg	kJ/kgK	kJ/kg	m3/kg
20	400	-1		(A5;B5;C5)	
10					
5					
1					
0,5					
0,1					

h_ptx_97

p in bar A5 = 20

t in °C B5 = 400

x in kg/kg C5 = -1

= 3248,227076

Formula result = 3248,23

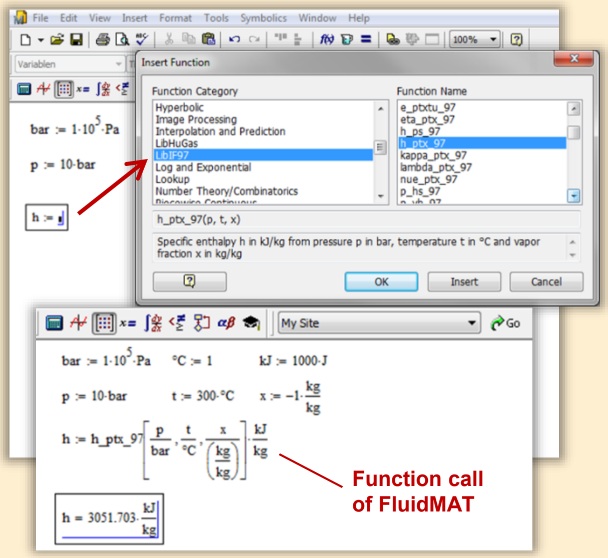
Or select a category: Water IAPWS-IF97

h_ptx_97(p in bar; t in °C; x in kg/kg)

Specific enthalpy h in kJ/kg.

Add-On FluidMAT for Mathcad®
Add-On FluidPRIME for Mathcad Prime®

The property libraries can be used in Mathcad® and Mathcad Prime®.



Function call of FluidMAT

h_ptx_97(p, t, x)

Specific enthalpy h in kJ/kg from pressure p in bar, temperature t in °C and vapor fraction x in kg/kg

$bar := 1\cdot10^5\cdot Pa$ $\quad °C := 1$ $\quad kJ := 1000\cdot J$

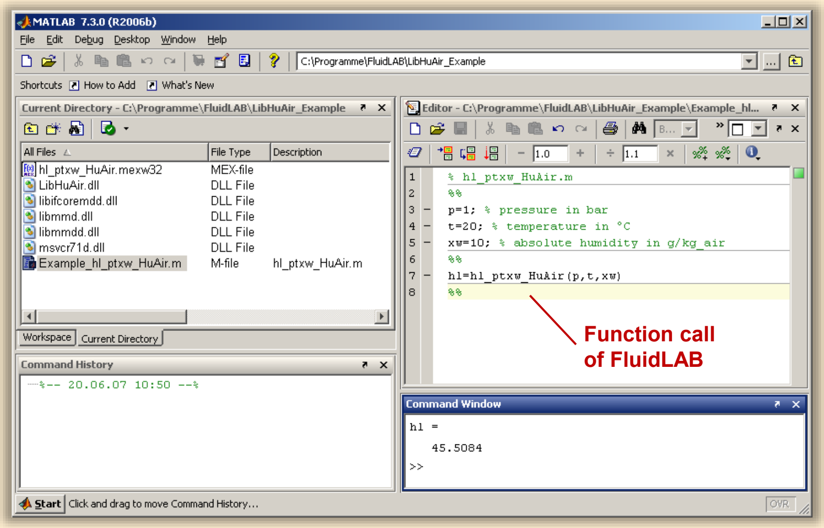
$p := 10\cdot bar$ $\quad t := 300\cdot °C$ $\quad x := -1\cdot\frac{kg}{kg}$

$$h := h\_ptx\_97\left(\frac{p}{bar}, \frac{t}{°C}, \frac{x}{\left(\frac{kg}{kg}\right)}\right)\cdot\frac{kJ}{kg}$$

$$h = 3051.703\cdot\frac{kJ}{kg}$$

Add-On FluidLAB for MATLAB® and SIMULINK®

Using the Add-In FluidLAB the property functions can be called in MATLAB® and SIMULINK®.



Function call of FluidLAB

```
% hl_ptxw_HuAir.m
%%
p=1; % pressure in bar
t=20; % temperature in °C
xw=10; % absolute humidity in g/kg_air
%%
hl=hl_ptxw_HuAir(p,t,xw)
%%
```

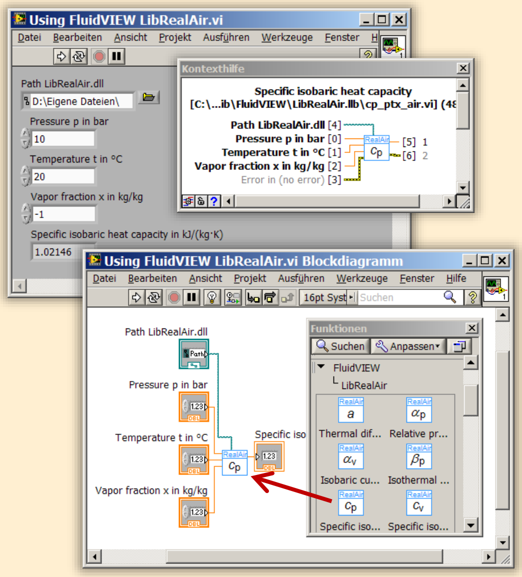
```
hl =

   45.5084

>>
```

Add-On FluidVIEW for LabVIEW™

The property functions can be calculated in LabVIEW™.



Pressure p in bar: 10

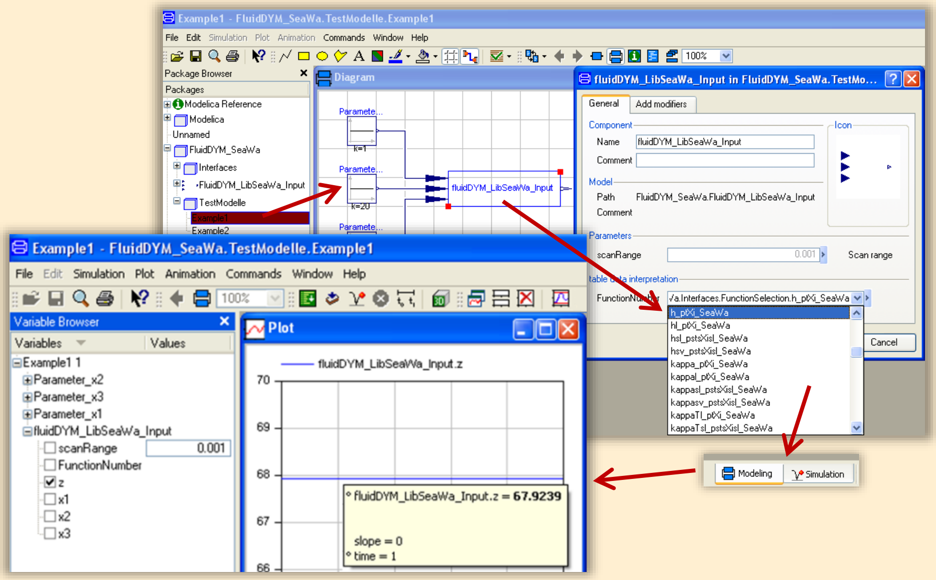
Temperature t in °C: 20

Vapor fraction x in kg/kg: -1

Specific isobaric heat capacity in kJ/(kg·K): 1.02146

Add-On FluidDYM for DYMOLA® (Modelica) and SimulationX®

The property functions can be called in DYMOLA® and SimulationX®.



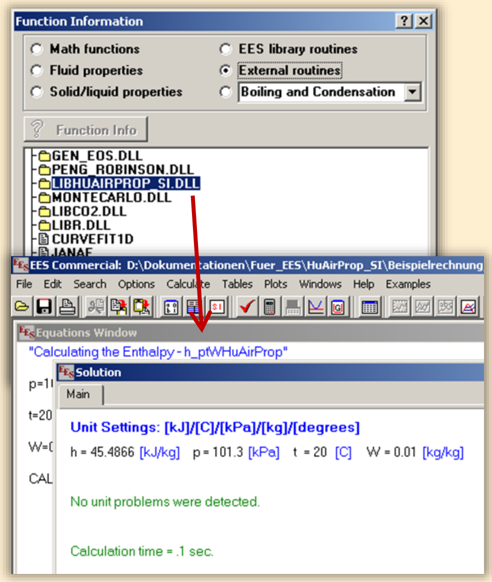
scanRange 0.001

fluidDYM_LibSeaWa_Input.z = 67.9239

slope = 0

time = 1

Add-On FluidEES for Engineering Equation Solver®



"Calculating the Enthalpy - h_ptWHuAirProp"

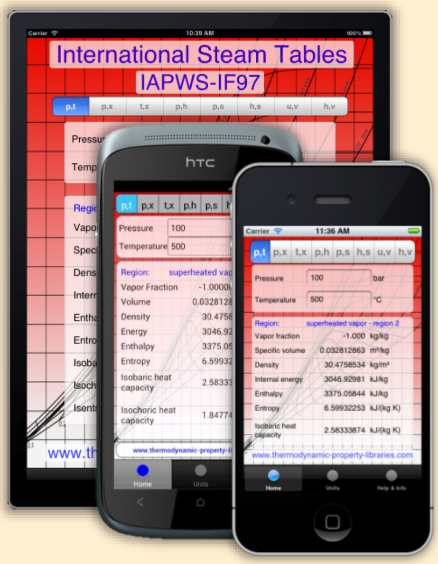
Unit Settings: [kJ]/[C]/[kPa]/[kg]/[degrees]

h = 45.4866 [kJ/kg]   p = 101.3 [kPa]   t = 20 [C]   W = 0.01 [kg/kg]

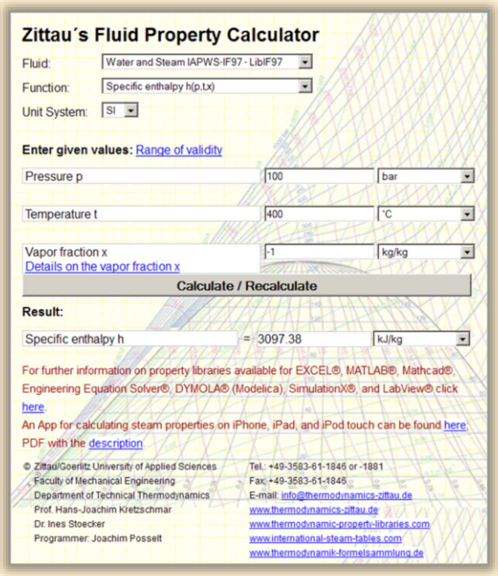
No unit problems were detected.

Calculation time = .1 sec.

App International Steam Tables for iPhone, iPad, iPod touch, Android Smartphones and Tablets



Online Property Calculator at www.thermofluidprop.com



Zittau´s Fluid Property Calculator

Fluid: Water and Steam IAPWS-IF97 - LibIF97

Function: Specific enthalpy h(p,t,x)

Unit System: SI

Enter given values: Range of validity

Pressure p	100	bar
Temperature t	400	°C
Vapor fraction x Details on the vapor fraction x	-1	kg/kg

Calculate / Recalculate

Result:

Specific enthalpy h = 3097.38 kJ/kg

For further information on property libraries available for EXCEL®, MATLAB®, Mathcad®, Engineering Equation Solver®, DYMOLA® (Modelica), SimulationX®, and LabView® click here.

An App for calculating steam properties on iPhone, iPad, and iPod touch can be found here; PDF with the description.

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Dr. Ines Stoecker
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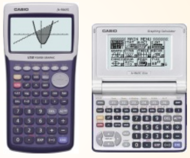
www.thermodynamics-zittau.de
www.thermodynamic-property-libraries.com
www.international-steam-tables.com
www.thermodynamik-formelsammlung.de

Property Software for Pocket Calculators

FluidCasio


fx 9750 G II


CFX 9850
fx-GG20


CFX 9860 G
Graph 85


ALGEBRA
FX 2.0

FluidHP


HP 48

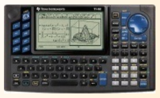

HP 49

FluidTI


TI Nspire CX CAS
TI Nspire CAS


TI 83
TI 84
TI 89


TI Voyage 200


TI 92

For more information please contact:

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Fax: +49-3222-1095810

The following thermodynamic and transport properties[a] can be calculated in Excel®, MATLAB®, Mathcad®, Engineering Equation Solver® (EES), DYMOLA® (Modelica), SimulationX® and LabVIEW™:

Thermodynamic Properties

- Vapor pressure p_s
- Saturation temperature T_s
- Density ρ
- Specific volume v
- Enthalpy h
- Internal energy u
- Entropy s
- Exergy e
- Isobaric heat capacity c_p
- Isochoric heat capacity c_v
- Isentropic exponent κ
- Speed of sound w
- Surface tension σ

Transport Properties

- Dynamic viscosity η
- Kinematic viscosity ν
- Thermal conductivity λ
- Prandtl number Pr
- Thermal diffusivity a

Backward Functions

- T, v, s (p,h)
- T, v, h (p,s)
- p, T, v (h,s)
- p, T (v,h)
- p, T (v,u)

Thermodynamic Derivatives

- Partial derivatives used in process modeling can be calculated.

---

[a] Not all of these property functions are available in all property libraries.

www.thermofluidprop.com

5 References

[1] Herrmann, S.; Kretzschmar, H.-J.; Gatley, D.P.: Thermodynamic Properties of Real Moist Air, Dry Air, Steam, Water, and Ice. HVAC&R Research 5, 961-986 (2009).

[2] Herrmann, S.; Kretzschmar, H.-J.; Gatley, D.P.: Thermodynamic Properties of Real Moist Air, Dry Air, Steam, Water, and Ice. ASHRAE RP-1485, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, GA (2009).

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[11] IAPWS. R14-08, Revised Release on the Pressure along the Melting and Sublimation Curves of Ordinary Water Substance. (2008); available from www.iapws.org.

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[16] IAPWS. G7-04, Guideline on the Henry's Constant and Vapor-Liquid Distribution Constant for Gases in H_2O and D_2O at High Temperatures. (2004), available from www.iapws.org.

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6 Satisfied Customers

Period from 2018 to 2022

The following companies and institutions use the property libraries:

- FluidEXL^{Graphics} for Excel® incl. VBA
- FluidLAB for MATLAB® and Simulink
- FluidMAT for Mathcad®
- FluidPRIME for Mathcad Prime®
- FluidEES for Engineering Equation Solver® EES
- FluidDYM for Dymola® (Modelica) and SimulationX®
- FluidVIEW for LabVIEW™
- FluidPYT for Python
- FluidJAVA for Java
- DLLs for Windows Applications
- Shared Objects for Linux
- Shared Objects for macOS.

2022

ASTG, Graz, Austria	12/2022
Wandschneider + Gutjahr, Hamburg	
RWE Supply & Trading, Essen	11/2022
Stadtwerke Rosenheim	
CEA, Saclay, France	10/2022
RWE Supply & Trading, Essen	
SEEC Saudi Energy Efficiency Center, Riyadh, Saudi Arabia	
MAN, Copenhagen, Denmark	
Hermeler & Partner Consulting Engineers, Sassenberg	09/2022
Envi Con, Nürnberg	
Drill Cool Systems, Bakersfield CA, USA	
RWE Supply & Trading, Essen	
Maerz Ofenbau, Zürich, Switzerland	
Saale Energie, Schkopau	
ERGO, Dresden	
Mainova, Frankfurt/Main	
Bundeswehr, Koblenz	08/2022
RWE Supply & Trading, Essen	
Grenzebach Corporation, Newnan GE, USA	
AGRANA, Gmuend, Austria	07/2022
MIBRAG, Zeitz	
Hochschule Niederrhein, Krefeld	
ULT, Löbau	06/2022
LEAG, Cottbus	

VPC Group, Vetschau	
Wärme, Hamburg	
ILK, Dresden	
Stricker IB, Küssnacht a. Rigi, Switzerland	
LEAG, Cottbus	05/2022
RWE Supply & Trading, Essen	
IGT Tomalla, Kreuztal	
B+T Engineering, Dübendorf, Switzerland	
Stricker IB, Küssnacht a. Rigi, Switzerland	
Vogelsang & Benning, Bochum	04/2022
Frischli, Rehburg-Loccum	
BPS Consulting, Sprenge	03/2022
HS Hannover, Maschinenbau & BioVT	
M+M Turbinentechnik, Bad Salzuflen	
Uni. Strathclyde, Glasgow, UK	02/2022
Delta Energy Group, Jiaozhou City, Qingdao, China	
Wetzel IB, Guben	
Wijbenga, PC Geldermalsen, The Netherlands	
Voith Paper, Heidenheim	
HS Zittau/Görlitz, Maschinenwesen	01/2022
Thermische Abfallbehandlung, Lauta	
Webb Institute, Glen Cove NY, USA	
TU Berlin, Umweltverfahrenstechnik	
SachsenEnergie, Dresden	
Doosan, Chang-won-si, Gyeongsangnam-do, South Korea	
KW3, LH Veenendaal, The Netherlands	
Université du Luxembourg, Esch-sur-Alzette	
Enseleit IB, Mansfeld	
Caliqua/Equans, Zürich, Switzerland	
Rudnick & Enners, Alpenrod	

2021

Wenisch IB, Vetschau	12/2021
PPCHEM, Hinwil, Switzerland	
KW3, The Netherlands	
BASF Ludwigshafen	
Air-Consult, Jena	
Sjerp & Jongeneel, RB Zoetermeer, The Netherlands	11/2021
Maerz Ofenbau, Zürich, Switzerland	
RWE Supply & Trading, Essen	
Hahn IB, Dresden	10/2021
Therm, South Africa	
RWE Supply & Trading, Essen	
TH Nürnberg, Verfahrenstechnik	09/2021
RWE Supply & Trading, Essen	
Enseleit IB, Mansfeld	

SachsenEnergie, Dresden	
BSH Hausgeräte, Berlin	
Norsk Energi, Oslo, Norway	08/2021
AKM Industrieanlagen, Haltern	
Drill Cool Systems, Bakersfield CA, USA	
Siemens Energy Global, Erlangen	07/2021
Wulff & Umag, Husum	
Planungsbüro Waidhas, Chemnitz	
Burkhardt Energie Technik, Mühlhausen	
Lücke IB, Paderborn	06/2021
TU Dresden, Energieverfahrenstechnik	
Wärme, Hamburg	
AL-KO Therm, Kötz	
PCK Raffinerie, Schwedt	
Vogelsang & Benning, Bochum	05/2021
MTU, München	
VPC Group, Vetschau	
AVG, Köln	04/2021
TH Ulm, Institut für Fahrzeugtechnik	
Marty IB, Oberwil, Switzerland	
HypTec, Lebring, Austria	
Lopez IB, Getxo, Bizkaia, Spain	03/2021
GM Remediation Systems, Leoben, Austria	
Jager Kältetechnik, Osnabrück	
T&M Automation, GR Leidschendam, The Netherlands	
RWE Supply & Trading, Essen	
Stadtwerke Leipzig	
Beuth Hochschule für Technik, Berlin	
Beleth IB, Woeth	02/2021
ZTL, Thal, Austria	
ETABO Bochum	
RWE Supply & Trading, Essen	
Onyx Germany, Berlin	
TU Dresden, Kältetechnik	
GOHL-KTK, Durmersheim	
Therm Development, South Africa	
thermofin, Heinsdorfergrund	
RWE Supply & Trading, Essen	01/2021
STEAG, Essen	
ETA Energieberatung, Pfaffenhofen	
Enex Power, Kirchseeon	

2020

Drill Cool, Bakersfield CA, USA	12/2020
Manders, The Netherlands	
RWE Supply & Tranding, Essen	

NEOWAT Lodz, Poland	
University of Duisburg-Essen, Duisburg	11/2020
Stellenbosch University, South Africa	
University De France-COMTe, France	
RWE, Essen	
STEAG, Herne	
Isenmann Ingenierbüro	
University of Stuttgart, ITLR, Stuttgart	
Norsk Energi, Oslo, Norway	
TGM Kanis, Nürnberg	
Stadtwerke Neuburg	10/2020
Smurfit Kappa, Roermond, The Netherlands	
RWE, Essen	
Hochschule Zittau/Görlitz, Wirtschaftsingenieurwesen	
Stadtwerke, Neuburg	
ILK, Dresden	
ATESTEO, Alsdorf	
Hochschule Zittau/Görlitz, Maschinenwesen	
TH Nürnberg, Verfahrenstechnik	
Drill Cool, Bakersfield CA,USA	09/2020
RWE, Essen	
2Meyers Ingenieurbüro, Nürnberg	
FELUWA, Mürlenbach	
Stadtwerke Neuburg	
Caverion, Wien, Austria	
GMVA Niederrhein, Oberhausen	
INWAT Lodz, Poland	
Troche Ingenieurbüro, Hayingen	08/2020
CEA Saclay, France	
VPC, Vetschau	07/2020
FSK System-Kälte-Klima, Dortmund	
Exergie Etudes, Sarl, Switzerland	
AWG Wuppertal	
STEAG Energy Services, Zwingenberg	
Hochschule Braunschweig	06/2020
DBI, Leipzig	
GOHL-KTK, Dumersheim	
TU Dresden, Energieverfahrenstechnik	
BASF SE, ESI/EE, Ludwigshafen	
Wärme Hamburg	
Ruchti Ingenieurbüro, Uster, Switzerland	
IWB, Basel, Switzerland	
Midiplan, Bietingen-Bissingen	05/2020
Knieschke, Ingenieurbüro	
RWE, Essen	
Leser, Hamburg	

AGRANA, Gmünd, Austria	
EWT Wassertechnik, Celle	
Hochschule Darmstadt	04/2020
MTU München CCP	
HAW Hamburg	03/2020
Hanon, Novi Jicin, Czech Republic	
TU Dresden, Kältetechnik	
MAN, Copenhagen, Denmark	
EnerTech, Radebeul	02/2020
LEAG, Cottbus	
B+B Enginering Magdeburg	
Hochschule Offenburg	
WIB, Dennheritz	01/2020
Universität Duisburg-Essen, Strömungsmaschinen	
Kältetechnik Dresen-Bremen	
TH Ingolstadt	
Vattenfall AB, Jokkmokk, Sweden	
Fraunhofer UMSICHT	

2019

PEU Leipzig, Rötha	12/2019
MB-Holding, Vestenbergsgreuth	
RWE, Essen	
Georg-Büchner-Hochschule, Darmstadt	11/2019
EEB ENERKO, Aldenhoven	
Robert Benoufa Energietechnik, Wiesloch	
Kehrein & Kubanek Klimatechnik, Moers	10/2019
Hanon Systems Autopal Services, Hluk, Czech Republic	
CEA Saclay, Gif Sur Yvette cedex, France	
Saudi Energy Efficiency Center SEEC, Riyadh, Saudi Arabia	
VPC, Vetschau	09/2019
jGanser PM + Engineering, Forchheim	
Endress+Hauser Flowtec AG, Reinach, Switzerland	
Ruchti IB, Uster, Switzerland	
ZWILAG Zwischenlager Würenlingen, Switzerland	08/2019
Hochschule Zittau/Görlitz, Faculty Maschinenwesen	
Stadtwerke Neubrandenburg	
Physikalisch Technische Bundesanstalt PTB, Braunschweig	
GMVA Oberhausen	07/2019
Endress+Hauser Flowtec AG, Reinach, Switzerland	
WARNICA, Waterloo, Canada	
MIBRAG, Zeitz	06/2019
Pöyry, Zürich, Switzerland	
RWTH Aachen, Institut für Strahlantriebe und Turbomaschinen	
Midiplan, Bietigheim-Bissingen	
GKS Schweinfurt	

HS Zittau/Görlitz, Wirtschaftswissenschaften und Wirtschaftsingenieurwesen	
ILK Dresden	
HZDR Helmholtz Zentrum Dresden-Rossendorf	
TH Köln, Technische Gebäudeausrüstung	05/2019
IB Knittel, Braunschweig	
Norsk Energi, Oslo, Norway	
STEAG, Essen	
Stora Enso, Eilenburg	
IB Lücke, Paderborn	
Haarslev, Sonderso, Denmark	
MAN Augsburg	
Wieland Werke, Ulm	04/2019
Fels-Werke, Elbingerode	
Univ. Luxembourg, Luxembourg	
BTU Cottbus, Power Engineering	03/2009
Eins-Energie Sachsen, Schwarzenberg	
TU Dresden, Kälte- und Kryotechnik	
ITER, St. Paul Lez Durance Cedex, France	
Fraunhofer UMSICHT, Oberhausen	
Comparex Leipzig for Spedition Thiele HEMMERSBACH	
Rückert NaturGas, Lauf/Pegnitz	
BASF, Basel, Switzerland	02/2019
Stadtwerke Leipzig	
Maerz Ofenbau Zürich, Switzerland	
Hanon Systems Germany, Kerpen	
Thermofin, Heinsdorfergrund	01/2019
BSH Berlin	

2018

Jaguar Energy, Guatemala	12/2018
WEBASTO, Gilching	
Smurfit Kappa, Oosterhout, Netherlands	
Univ. BW München	
RAIV, Liberec for VALEO, Prague, Czech Republic	11/2018
VPC Group Vetschau	
SEITZ, Wetzikon, Switzerland	
MVV, Mannheim	10/2018
IB Troche	
KANIS Turbinen, Nürnberg	
TH Ingolstadt, Institut für neue Energiesysteme	
IB Kristl & Seibt, Graz, Austria	09/2018
INEOS, Köln	
IB Lücke, Paderborn	
Südzucker, Ochsenfurt	08/2018
K&K Turbinenservice, Bielefeld	07/2018
OTH Regensburg, Elektrotechnik	

Comparex Leipzig for LEAG, Berlin	06/2018
Münstermann, Telgte	05/2018
TH Nürnberg, Verfahrenstechnik	
Universität Madrid, Madrid, Spanien	
HS Zittau/Görlitz, Wirtschaftsingenieurwesen	
HS Niederrhein, Krefeld	
Wilhelm-Büchner HS, Pfungstadt	03/2018
GRS, Köln	
WIB, Dennheritz	
RONAL AG, Härklingen, Schweiz	02/2018
Ingenieurbüro Leipert, Riegelsberg	
AIXPROCESS, Aachen	
KRONES, Neutraubling	
Doosan Lentjes, Ratingen	01/2018

Part SI Units

1 Property Library ASHRAE-LibHuAirProp-SI

1.1 Function Overview

1.1.1 Function Overview for Real Moist Air

Functional Dependence	Function Name	Property or Function	Unit of the Result	Page
$a = \mathrm{f}(p,t,W)$	a_ptW_HAP_SI	Thermal diffusivity	m²/s	3/2
$\alpha_p = \mathrm{f}(p,t,W)$	alphap_ptW_HAP_SI	Relative pressure coefficient	1/K	3/3
$\beta_p = \mathrm{f}(p,t,W)$	betap_ptW_HAP_SI	Isothermal stress coefficient	kg/m³	3/4
$c = \mathrm{f}(p,t,W)$	c_ptW_HAP_SI	Speed of sound	m/s	3/5
$c_p = \mathrm{f}(p,t,W)$	cp_ptW_HAP_SI	Specific isobaric heat capacity	kJ/(kg·K)	3/6
$c_v = \mathrm{f}(p,t,W)$	cv_ptW_HAP_SI	Specific isochoric heat capacity	kJ/(kg·K)	3/7
$f = \mathrm{f}(p,t)$	f_pt_HAP_SI	Enhancement factor (decimal ratio)	-	3/8
$h = \mathrm{f}(p,t,W)$	h_ptW_HAP_SI	Air-specific enthalpy	kJ/kg$_a$	3/9
$\eta = \mathrm{f}(p,t,W)$	Eta_ptW_HAP_SI	Dynamic viscosity	Pa·s	3/10
$\kappa = \mathrm{f}(p,t,W)$	Kappa_ptW_HAP_SI	Isentropic exponent	-	3/11
$\lambda = \mathrm{f}(p,t,W)$	Lambda_ptW_HAP_SI	Thermal conductivity	W/(m·K)	3/12
$\nu = \mathrm{f}(p,t,W)$	Ny_ptW_HAP_SI	Kinematic viscosity	m²/s	3/13
$p = \mathrm{f}(t,s,W)$	p_tsW_HAP_SI	Pressure of humid air	kPa	3/14
$p = \mathrm{f}(z_{\mathrm{ele}})$	p_zele_HAP_SI	Pressure of humid air from elevation	kPa	3/15
$p_{\mathrm{Air}} = \mathrm{f}(p,t,W)$	pAIR_ptW_HAP_SI	Partial pressure of dry air in moist air	kPa	3/16
$p_{\mathrm{H2O}} = \mathrm{f}(p,t,W)$	pH2O_ptW_HAP_SI	Partial pressure of water vapor in moist air	kPa	3/17
$p_{\mathrm{H2Os}} = \mathrm{f}(p,t)$	pH2Os_pt_HAP_SI	Partial saturation pressure of water vapor	kPa	3/18

Functional Dependence	**Function Name**	**Property or Function**	**Unit of the Result**	**Page**
$\varphi = \mathrm{f}(p,t,W)$	phi_ptW_HAP_SI	Relative humidity (decimal ratio)	-	3/19
$Pr = \mathrm{f}(p,t,W)$	Pr_ptW_HAP_SI	PRANDTL number	-	3/20
$\psi_{Air} = \mathrm{f}(W)$	PsiAir_W_HAP_SI	Mole fraction of dry air in moist air	$\mathrm{mol_a/mol}$	3/21
$\psi_{\mathrm{H2O}} = \mathrm{f}(W)$	PsiH2O_W_HAP_SI	Mole fraction of water vapor in moist air	$\mathrm{mol_w/mol}$	3/22
$\rho = \mathrm{f}(p,t,W)$	Rho_ptW_HAP_SI	Density	$\mathrm{kg/m^3}$	3/23
$s = \mathrm{f}(p,t,W)$	s_ptW_HAP_SI	Air-specific entropy	$\mathrm{kJ/(kg_a \cdot K)}$	3/24
$t = \mathrm{f}(p,h,\varphi)$	t_phphi_HAP_SI	Backward function: temperature from total pressure, air-specific enthalpy and relative humidity	°C	3/25
$t = \mathrm{f}(p,h,W)$	t_phW_HAP_SI	Backward function: temperature from total pressure, air-specific enthalpy and humidity ratio	°C	3/26
$t = \mathrm{f}(p,s,W)$	t_psW_HAP_SI	Backward function: temperature from total pressure, air-specific entropy and humidity ratio	°C	3/27
$t = \mathrm{f}(p,t_{\mathrm{wb}},W)$	t_ptwbW_HAP_SI	Backward function: temperature from total pressure, wet-bulb temperature and humidity ratio	°C	3/28
$t_{\mathrm{d}} = \mathrm{f}(p,W)$	td_pW_HAP_SI	Dew-point/frost-point temperature	°C	3/29
$t_{\mathrm{s}} = \mathrm{f}(p,p_{\mathrm{H2O}})$	ts_ppH2O_HAP_SI	Backward function: saturation temperature of water from total pressure and partial pressure of water vapor	°C	3/30
$t_{\mathrm{wb}} = \mathrm{f}(p,t,W)$	twb_ptW_HAP_SI	Wet-bulb/ice-bulb temperature	°C	3/31
$u = \mathrm{f}(p,t,W)$	u_ptW_HAP_SI	Air-specific internal energy	$\mathrm{kJ/kg_a}$	3/32
$v = \mathrm{f}(p,t,W)$	v_ptW_HAP_SI	Air-specific volume	$\mathrm{m^3/kg_a}$	3/33
$W = \mathrm{f}(p,t,p_{\mathrm{H2O}})$	W_ptpH2O_HAP_SI	Humidity ratio from total pressure, temperature, and partial pressure of water vapor	$\mathrm{kg_w/kg_a}$	3/34
$W = \mathrm{f}(p,t,\varphi)$	W_ptphi_HAP_SI	Humidity ratio from total pressure, temperature, and relative humidity	$\mathrm{kg_w/kg_a}$	3/35
$W = \mathrm{f}(p,t_{\mathrm{d}})$	W_ptd_HAP_SI	Humidity ratio from total pressure and dew-point temperature	$\mathrm{kg_w/kg_a}$	3/36

Functional Dependence	**Function Name**	**Property or Function**	**Unit of the Result**	**Page**
$W = \mathrm{f}(p,t,t_{\mathrm{wb}})$	W_pttwb_HAP_SI	Humidity ratio from total pressure, (dry bulb) temperature, and wet-bulb temperature	$\mathrm{kg_w/kg_a}$	3/37
$W_{\mathrm{s}} = \mathrm{f}(p,t)$	Ws_pt_HAP_SI	Saturation humidity ratio	$\mathrm{kg_w/kg_a}$	3/38
$\xi_{\mathrm{Air}} = \mathrm{f}(W)$	XiAir_W_HAP_SI	Mass fraction of dry air in moist air	$\mathrm{kg_a/kg}$	3/39
$\xi_{\mathrm{H2O}} = \mathrm{f}(W)$	XiH2O_W_HAP_SI	Mass fraction of water vapor in moist air	$\mathrm{kg_w/kg}$	3/40
$Z = \mathrm{f}(p,t,W)$	Z_ptW_HAP_SI	Compression factor (decimal ratio)	-	3/41

Range of Validity of Thermodynamic Properties

Property	Range of Validity
Pressure:	$0.01 \le p \le 10\,000$ kPa
Temperature:	$-143.15 \le t \le 350$ °C
Humidity ratio:	$0 \le W \le 10$ $\mathrm{kg_w/kg_a}$
Relative humidity:	$0 \le \varphi \le 1$ (decimal ratio)
Dew-point temperature:	$-143.15 \le t_d \le 350$ °C
Wet-bulb temperature:	$-143.15 \le t_{wb} \le 350$ °C

Range of Validity of Transport Properties

Property	Range of Validity
Pressure:	$0.01 \le p \le 10\,000$ kPa
Temperature:	$-73.15 \le t \le 350$ °C
Humidity ratio:	$0 \le W \le 10$ $\mathrm{kg_w/kg_a}$
Relative humidity:	$0 \le \varphi \le 1$ (decimal ratio)

Molar Masses

Component	Molar Mass	Reference
Dry Air	28.966 kg/kmol	[17]
Water	18.015268 kg/kmol	[5], [6]

Reference States

Property	Dry Air	Steam, Water, and Ice
Pressure	101.325 kPa	$p_s(0.01°\mathrm{C}) = 0.611657$ kPa
Temperature	0°C	0.01°C
Enthalpy	0 kJ/kg	0.000611782 kJ/kg
Entropy	0 kJ/(kg K)	0 kJ/(kg K)

Units

Symbol	Quantity	Unit
p	Pressure	kPa
t	Temperature	°C
W	Humidity ratio	$\mathrm{kg_w/kg_a}$ (kg water / kg dry air)
φ	Relative humidity	(decimal ratio)
t_d	Dew point temperature	°C
t_{wb}	Wet bulb temperature	°C

1.1.2 Function Overview for Steam and Water for Temperatures $t \geq 0°C$

Functional Dependence	**Function Name**	**Property**	**Unit of the Result**	**Page**
$h_{liq} = f(p,t)$	hliq_pt_97_SI	Specific enthalpy of liquid water	kJ/kg	3/43
$h_{liq,s} = f(t)$	hliqs_t_97_SI	Specific enthalpy of saturated liquid water	kJ/kg	3/44
$h_{vap,s} = f(t)$	hvaps_t_97_SI	Specific enthalpy of saturated water vapor	kJ/kg	3/45
$p_s = f(t)$	ps_t_97_SI	Saturation pressure of water	kPa	3/46
$s_{liq} = f(p,t)$	sliq_pt_97_SI	Specific entropy of liquid water	kJ/(kg·K)	3/47
$s_{liq,s} = f(t)$	sliqs_t_97_SI	Specific entropy of saturated liquid water	kJ/(kg·K)	3/48
$s_{vap,s} = f(t)$	svaps_t_97_SI	Specific entropy of saturated water vapor	kJ/(kg·K)	3/49
$t_s = f(p)$	ts_p_97_SI	Saturation temperature of water	°C	3/50
$v_{liq} = f(p,t)$	vliq_pt_97_SI	Specific volume of liquid water	m^3/kg	3/51
$v_{liq,s} = f(t)$	vliqs_t_97_SI	Specific volume of saturated liquid water	m^3/kg	3/52
$v_{vap,s} = f(t)$	vvaps_t_97_SI	Specific volume of saturated water vapor	m^3/kg	3/53

Range of Validity

Property	Range of Validity
Pressure:	$0.01 \leq p \leq 10\,000$ kPa
Temperature:	$0 \leq t \leq 350$ °C

Units

Symbol	Quantity	Unit
p	Pressure	kPa
t	Temperature	°C

Reference State

Property	Water Vapor and Liquid Water
Pressure	p_s(0.01°C) = 0.611657 kPa
Temperature	0.01°C
Enthalpy	0.000611782 kJ/kg
Entropy	0 kJ/(kg K)

1.1.3 Function Overview for Steam and Ice for Temperatures $t \leq 0°C$

Functional Dependence	**Function Name**	**Property**	**Unit of the Result**	**Page**
$h_{ice,sub} = f(t)$	hicesub_t_06_SI	Specific enthalpy of saturated ice	kJ/kg	3/55
$h_{vap,sub} = f(t)$	hvapsub_t_95_SI	Specific enthalpy of saturated water vapor	kJ/kg	3/56
$p_{mel} = f(t)$	pmel_t_08_SI	Melting pressure of ice	kPa	3/57
$p_{sub} = f(t)$	psub_t_08_SI	Sublimation pressure of ice	kPa	3/58
$s_{ice,sub} = f(t)$	sicesub_t_06_SI	Specific entropy of saturated ice	kJ/(kg·K)	3/59
$s_{vap,sub} = f(t)$	svapsub_t_95_SI	Specific entropy of saturated water vapor	kJ/(kg·K)	3/60
$t_{mel} = f(p)$	tmel_p_08_SI	Melting temperature of ice	°C	3/61
$t_{sub} = f(p)$	tsub_p_08_SI	Sublimation temperature of ice	°C	3/62
$v_{ice,sub} = f(t)$	vicesub_t_06_SI	Specific volume of saturated ice	m³/kg	3/63
$v_{vap,sub} = f(t)$	vvapsub_t_95_SI	Specific volume of saturated water vapor	m³/kg	3/64

Range of Validity

Property	Range of Validity
Pressure:	$p_{\text{sub}}(-143.15°\text{C}) = 1.2002 \times 10^{-11} \le p \le 10\,000$ kPa
Temperature:	$-143.15 \le t \le 0$ °C

Units

Symbol	Quantity	Unit
p	Pressure	kPa
t	Temperature	°C

Reference State

Property	Water Vapor and Ice
Pressure	$p_s(0.01°\text{C}) = 0.611657$ kPa
Temperature	0.01°C
Enthalpy	0.000611782 kJ/kg
Entropy	0 kJ/(kg K)

1.2 Conversion of SI and I-P Units

Property		**Conversion: SI Units → I-P Units**	**Conversion: I-P Units → SI Units**	**Units SI**	**Units I-P**
Thermal diffusivity	a	$\frac{a_{\mathrm{IP}}}{\frac{\mathrm{ft^2}}{\mathrm{s}}} = \frac{a_{\mathrm{SI}}}{\frac{\mathrm{m^2}}{\mathrm{s}}} \times 10.76391042$	$\frac{a_{\mathrm{SI}}}{\frac{\mathrm{m^2}}{\mathrm{s}}} = \frac{a_{\mathrm{IP}}}{\frac{\mathrm{ft^2}}{\mathrm{s}}} \times 0.0929304$	m²/s	ft²/s
Relative pressure coefficient	α_p	$\frac{\alpha_{p,\mathrm{IP}}}{\frac{1}{\mathrm{°R}}} = \frac{\alpha_{p,\mathrm{SI}}}{\frac{1}{\mathrm{K}}} \times \frac{9}{5}$	$\frac{\alpha_{p,\mathrm{SI}}}{\frac{1}{\mathrm{K}}} = \frac{\alpha_{p,\mathrm{IP}}}{\frac{1}{\mathrm{°R}}} \times \frac{5}{9}$	1/K	1/°R
Isothermal stress coefficient	β_p	$\frac{\beta_{p,\mathrm{IP}}}{\frac{\mathrm{lb}}{\mathrm{ft^3}}} = \frac{\beta_{p,\mathrm{SI}}}{\frac{\mathrm{kg}}{\mathrm{m^3}}} \times 0.062428$	$\frac{\beta_{p,\mathrm{SI}}}{\frac{\mathrm{kg}}{\mathrm{m^3}}} = \frac{\beta_{p,\mathrm{IP}}}{\frac{\mathrm{lb}}{\mathrm{ft^3}}} \times 16.018463$	kg/m³	lb/ft³
Speed of sound	c	$\frac{c_{\mathrm{IP}}}{\frac{\mathrm{ft}}{\mathrm{s}}} = \frac{c_{\mathrm{SI}}}{\frac{\mathrm{m}}{\mathrm{s}}} \times 3.2808399$	$\frac{c_{\mathrm{SI}}}{\frac{\mathrm{m}}{\mathrm{s}}} = \frac{c_{\mathrm{IP}}}{\frac{\mathrm{ft}}{\mathrm{s}}} \times 0.3048$	m/s	ft/s
Specific isobaric heat capacity	c_p	$\frac{c_{p,\mathrm{IP}}}{\frac{\mathrm{Btu}}{\mathrm{lb\ °R}}} = \frac{c_{p,\mathrm{SI}}}{\frac{\mathrm{kJ}}{\mathrm{kg\ K}}} \times 0.2388459$	$\frac{c_{p,\mathrm{SI}}}{\frac{\mathrm{kJ}}{\mathrm{kg\ K}}} = \frac{c_{p,\mathrm{IP}}}{\frac{\mathrm{Btu}}{\mathrm{lb\ °R}}} \times 4.1868$	kJ/(kg·K)	Btu/(lb·°R)
Specific isochoric heat capacity	c_v	$\frac{c_{v,\mathrm{IP}}}{\frac{\mathrm{Btu}}{\mathrm{lb\ °R}}} = \frac{c_{v,\mathrm{SI}}}{\frac{\mathrm{kJ}}{\mathrm{kg\ K}}} \times 0.2388459$	$\frac{c_{v,\mathrm{SI}}}{\frac{\mathrm{kJ}}{\mathrm{kg\ K}}} = \frac{c_{v,\mathrm{IP}}}{\frac{\mathrm{Btu}}{\mathrm{lb\ °R}}} \times 4.1868$	kJ/(kg·K)	Btu/(lb·°R)
Dynamic viscosity	η	$\frac{\eta_{\mathrm{IP}}}{\frac{\mathrm{lb\ s}}{\mathrm{ft^2}}} = \frac{\eta_{\mathrm{SI}}}{\frac{\mathrm{Pa}}{\mathrm{s}}} \times 0.02088543$	$\frac{\eta_{\mathrm{SI}}}{\frac{\mathrm{Pa}}{\mathrm{s}}} = \frac{\eta_{\mathrm{IP}}}{\frac{\mathrm{lb\ s}}{\mathrm{ft^2}}} \times 47.880259$	Pa·s	lb·s/ft²
Enhancement factor	f	$f_{\mathrm{IP}} = f_{\mathrm{SI}}$	$f_{\mathrm{SI}} = f_{\mathrm{IP}}$	-	-

Property		**Conversion: SI Units → I-P Units**	**Conversion: I-P Units → SI Units**	**Units SI**	**Units I-P**
Air-specific enthalpy (moist air)	h	$\dfrac{h_{\mathrm{IP}}}{\frac{\mathrm{Btu}}{\mathrm{lb_a}}} = \dfrac{h_{\mathrm{SI}}}{\frac{\mathrm{kJ}}{\mathrm{kg_a}}} \times 0.4299226 + 7.68565365666$	$\dfrac{h_{\mathrm{SI}}}{\frac{\mathrm{kJ}}{\mathrm{kg_a}}} = \left(\dfrac{h_{\mathrm{IP}}}{\frac{\mathrm{Btu}}{\mathrm{lb_a}}} - 7.68565365666\right) \times 2.326$	kJ/kg$_a$	Btu/lb$_a$
Specific enthalpy (water, water vapor, ice)	h_w	$\dfrac{h_{\mathrm{IP}}}{\frac{\mathrm{Btu}}{\mathrm{lb}}} = \dfrac{h_{\mathrm{SI}}}{\frac{\mathrm{kJ}}{\mathrm{kg}}} \times 0.4299226$	$\dfrac{h_{\mathrm{SI}}}{\frac{\mathrm{kJ}}{\mathrm{kg}}} = \dfrac{h_{\mathrm{IP}}}{\frac{\mathrm{Btu}}{\mathrm{lb}}} \times 2.326$	kJ/kg	Btu/lb
Isentropic exponent	κ	$\kappa_{\mathrm{IP}} = \kappa_{\mathrm{SI}}$	$\kappa_{\mathrm{SI}} = \kappa_{\mathrm{IP}}$	-	-
Thermal conductivity	λ	$\dfrac{\lambda_{\mathrm{IP}}}{\frac{\mathrm{Btu}}{\mathrm{h\ ft\ °R}}} = \dfrac{\lambda_{\mathrm{SI}}}{\frac{\mathrm{W}}{\mathrm{m\ K}}} \times 0.57778932$	$\dfrac{\lambda_{\mathrm{SI}}}{\frac{\mathrm{W}}{\mathrm{m\ K}}} = \dfrac{\lambda_{\mathrm{IP}}}{\frac{\mathrm{Btu}}{\mathrm{h\ ft\ °R}}} \times 1.73073467$	W/(m·K)	Btu/(h·ft·°R)
Kinematic viscosity	ν	$\dfrac{\nu_{\mathrm{IP}}}{\frac{\mathrm{ft^2}}{\mathrm{s}}} = \dfrac{\nu_{\mathrm{SI}}}{\frac{\mathrm{m^2}}{\mathrm{s}}} \times 10.763910417$	$\dfrac{\nu_{\mathrm{SI}}}{\frac{\mathrm{m^2}}{\mathrm{s}}} = \dfrac{\nu_{\mathrm{IP}}}{\frac{\mathrm{ft^2}}{\mathrm{s}}} \times 0.092903040$	m²/s	ft²/s
Pressure	p	$\dfrac{p_{\mathrm{IP}}}{\mathrm{psi}} = \dfrac{p_{\mathrm{SI}}}{\mathrm{kPa}} \times 0.14503774$	$\dfrac{p_{\mathrm{SI}}}{\mathrm{kPa}} = \dfrac{p_{\mathrm{IP}}}{\mathrm{psi}} \times 6.894757$	kPa	psi
Relative humidity	φ	$\varphi_{\mathrm{IP}} = \varphi_{\mathrm{SI}}$	$\varphi_{\mathrm{SI}} = \varphi_{\mathrm{IP}}$	-	-
Prandtl number	Pr	$Pr_{\mathrm{IP}} = Pr_{\mathrm{IP}}$	$Pr_{\mathrm{SI}} = Pr_{\mathrm{IP}}$	-	-
Mole fraction	ψ	$\psi_{\mathrm{IP}} = \psi_{\mathrm{SI}}$	$\psi_{\mathrm{SI}} = \psi_{\mathrm{IP}}$	mol/mol	mol/mol
Density	ρ	$\dfrac{\rho_{\mathrm{IP}}}{\frac{\mathrm{lb}}{\mathrm{ft^3}}} = \dfrac{\rho_{\mathrm{SI}}}{\frac{\mathrm{kg}}{\mathrm{m^3}}} \times 0.062428$	$\dfrac{\rho_{\mathrm{SI}}}{\frac{\mathrm{kg}}{\mathrm{m^3}}} = \dfrac{\rho_{\mathrm{IP}}}{\frac{\mathrm{lb}}{\mathrm{ft^3}}} \times 16.018463$	kg/m³	lb/ft³
Air-specific entropy (moist air)	s	$\dfrac{s_{\mathrm{IP}}}{\frac{\mathrm{Btu}}{\mathrm{lb_a\ °R}}} = \dfrac{s_{\mathrm{SI}}}{\frac{\mathrm{kJ}}{\mathrm{kg_a\ K}}} \times 0.2388459 + 0.01616365106$	$\dfrac{s_{\mathrm{SI}}}{\frac{\mathrm{kJ}}{\mathrm{kg_a\ K}}} = \left(\dfrac{s_{\mathrm{IP}}}{\frac{\mathrm{Btu}}{\mathrm{lb_a\ °R}}} - 0.01616365106\right) \times 4.1868$	kJ/(kg$_a$·K)	Btu/(lb$_a$·°R)

Property		Conversion: SI Units → I-P Units	Conversion: I-P Units → SI Units	Units SI	Units I-P
Specific entropy (water, water vapor, ice)	s_w	$\frac{s_{\mathrm{IP}}}{\frac{\mathrm{Btu}}{\mathrm{lb_a}\ ^\circ\mathrm{R}}} = \frac{s_{\mathrm{SI}}}{\frac{\mathrm{kJ}}{\mathrm{kg_a}\ \mathrm{K}}} \times 0.23884589$	$\frac{s_{\mathrm{SI}}}{\frac{\mathrm{kJ}}{\mathrm{kg_a}\ \mathrm{K}}} = \frac{s_{\mathrm{IP}}}{\frac{\mathrm{Btu}}{\mathrm{lb_a}\ ^\circ\mathrm{R}}} \times 4.1868$	$\mathrm{kJ/(kg_a \cdot K)}$	$\mathrm{Btu/(lb_a \cdot {}^\circ R)}$
Temperature	t	$\frac{t_{\mathrm{IP}}}{^\circ\mathrm{F}} = \frac{t_{\mathrm{SI}}}{^\circ\mathrm{C}} \times \frac{9}{5} + 32$	$\frac{t_{\mathrm{SI}}}{^\circ\mathrm{C}} = \left(\frac{t_{\mathrm{IP}}}{^\circ\mathrm{F}} - 32\right) \times \frac{5}{9}$	°C	°F
Air-specific internal energy (moist air)	u	$(u = h - pv)$ $\frac{u_{\mathrm{IP}}}{\frac{\mathrm{Btu}}{\mathrm{lb_a}}} = \frac{h_{\mathrm{SI}}}{\frac{\mathrm{kJ}}{\mathrm{kg_a}}} \times 0.4299226 + 7.68565365666$ $- \frac{p_{\mathrm{SI}}}{\mathrm{kPa}} \times 0.145037738 \cdot \frac{v_{\mathrm{SI}}}{\frac{\mathrm{m^3}}{\mathrm{kg_a}}} \times 16.018453$	$(u = h - pv)$ $\frac{u_{\mathrm{SI}}}{\frac{\mathrm{kJ}}{\mathrm{kg_a}}} = \left(\frac{h_{\mathrm{IP}}}{\frac{\mathrm{Btu}}{\mathrm{lb_a}}} - 7.68565365666\right) \times 2.236$ $- \frac{p_{\mathrm{IP}}}{\mathrm{psi}} \times 6.894757293 \cdot \frac{v_{\mathrm{SIP}}}{\frac{\mathrm{ft^3}}{\mathrm{lb_a}}} \times 0.062428$	$\mathrm{kJ/kg_a}$	$\mathrm{Btu/lb_a}$
Air-specific volume (moist air)	v	$\frac{v_{\mathrm{IP}}}{\frac{\mathrm{ft^3}}{\mathrm{lb_a}}} = \frac{v_{\mathrm{SI}}}{\frac{\mathrm{m^3}}{\mathrm{kg_a}}} \times 16.018453$	$\frac{v_{\mathrm{SI}}}{\frac{\mathrm{m^3}}{\mathrm{kg_a}}} = \frac{v_{\mathrm{IP}}}{\frac{\mathrm{ft^3}}{\mathrm{lb_a}}} \times 0.062428$	$\mathrm{m^3/kg_a}$	$\mathrm{ft^3/lb_a}$
Specific volume (water, water vapor, ice)	v_w	$\frac{v_{\mathrm{IP}}}{\frac{\mathrm{ft^3}}{\mathrm{lb}}} = \frac{v_{\mathrm{SI}}}{\frac{\mathrm{m^3}}{\mathrm{kg}}} \times 16.018453$	$\frac{v_{\mathrm{SI}}}{\frac{\mathrm{m^3}}{\mathrm{kg}}} = \frac{v_{\mathrm{IP}}}{\frac{\mathrm{ft^3}}{\mathrm{lb}}} \times 0.062428$	$\mathrm{m^3/kg}$	$\mathrm{ft^3/lb}$
Humidity ratio	W	$W_{\mathrm{IP}} = W_{\mathrm{SI}}$	$W_{\mathrm{SI}} = W_{\mathrm{IP}}$	$\mathrm{kg_w/kg_a}$	$\mathrm{lb_w/lb_a}$
Mass fraction	ξ	$\xi_{\mathrm{IP}} = \xi_{\mathrm{SI}}$	$\xi_{\mathrm{SI}} = \xi_{\mathrm{IP}}$	$\mathrm{kg_w/kg}$	$\mathrm{lb_w/lb}$
Compression factor	Z	$Z_{\mathrm{IP}} = Z_{\mathrm{SI}}$	$Z_{\mathrm{SI}} = Z_{\mathrm{IP}}$	-	-

1.3 Calculation Algorithms

1.3.1 Algorithms for Real Moist Air

The properties of moist air are calculated from the modified Hyland-Wexler model given in Herrmann, Kretzschmar, and Gatley (HKG) [1], [2]. The modifications incorporate:

- the value for the universal molar gas constant from the CODATA standard by Mohr and Taylor [22]
- the value for the molar mass of dry air from Gatley et al. [17] and that of water from IAPWS-95 [5], [6]
- the calculation of the ideal-gas parts of the heat capacity, enthalpy, and entropy for dry air from the fundamental equation of Lemmon et al. [14]
- the calculation of the ideal-gas parts of the heat capacity, enthalpy, and entropy for water vapor from IAPWS-IF97 [7], [8], [9] for $t \geq 0°\mathrm{C}$ and from IAPWS-95 [5], [6] for $t \leq 0°\mathrm{C}$
- the calculation of the vapor-pressure enhancement factor from the equation given by the models of Hyland and Wexler [21]
- the 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. [14] according to Feistel et al. [24]
- the calculation of the second and third molar virial coefficients B_{ww} and C_{www} for water and steam from IAPWS-95 [5], [6] according to Feistel et al. [24]
- the calculation of the air-water second molar cross-virial coefficient B_{aw} from Harvey and Huang [15]
- the calculation of the air-water third molar cross-virial coefficients C_{aaw} and C_{aww} from Nelson and Sauer [12], [13]
- the calculation of the saturation pressure of water from IAPWS-IF97 [7], [8], [9] for $t \geq 0°\mathrm{C}$ and of the sublimation pressure of water from IAPWS-08 [11] for $t \leq 0°\mathrm{C}$
- the calculation of the isothermal compressibility of saturated liquid water from IAPWS-IF97 [7], [8], [9] for $t \geq 0°\mathrm{C}$ and that of ice from IAPWS-06 [10] for $t \leq 0°\mathrm{C}$ in the determination of the vapor-pressure enhancement factor
- the calculation of Henry's constant from the IAPWS Guideline 2004 [16] in the determination of the enhancement factor. The mole fractions for the three main components of dry air were taken from Lemmon et al. [14]. Argon was not considered in the calculation of Henry’s constant in the former research projects, but it is now the third component of dry air.

The transport properties of moist air are calculated from the model given in Herrmann et al. [3], [4].

1.3.2 Algorithms for Steam and Water for Temperatures $t \geq 0°C$

The p-T diagram in Fig. 1 shows the formulations used for water and water vapor. The temperature range above 0°C is covered by IAPWS-IF97 [7], [8], [9]:

- The saturation line is calculated from the IAPWS-IF97 saturation pressure equation $p_s^{97}(t)$ and saturation temperature equation $t_s^{97}(p)$.
- The properties in the liquid region including saturated-liquid line are calculated from the fundamental equation of the IAPWS-IF97 region 1.
- The properties in the vapor region including saturated-vapor line are calculated from the fundamental equation of the IAPWS-IF97 region 2.

1.3.3 Algorithms for Steam and Ice for Temperatures $t \leq 0°C$

- The sublimation curve is covered by the IAPWS-08 sublimation pressure equation $p_{\mathrm{subl}}^{08}(t)$ [11] (see Fig. 1).
- The properties of ice including saturated ice are determined by the fundamental equation of the IAPWS-06 [10].
- The properties of vapor including saturated vapor are calculated from the fundamental equation of IAPWS-95 [5], [6].

1.3.4 Overview of the Applied Formulations for Steam, Water, and Ice

The following p-T diagram shows the used IAPWS Formulations and the ranges where they are applied.

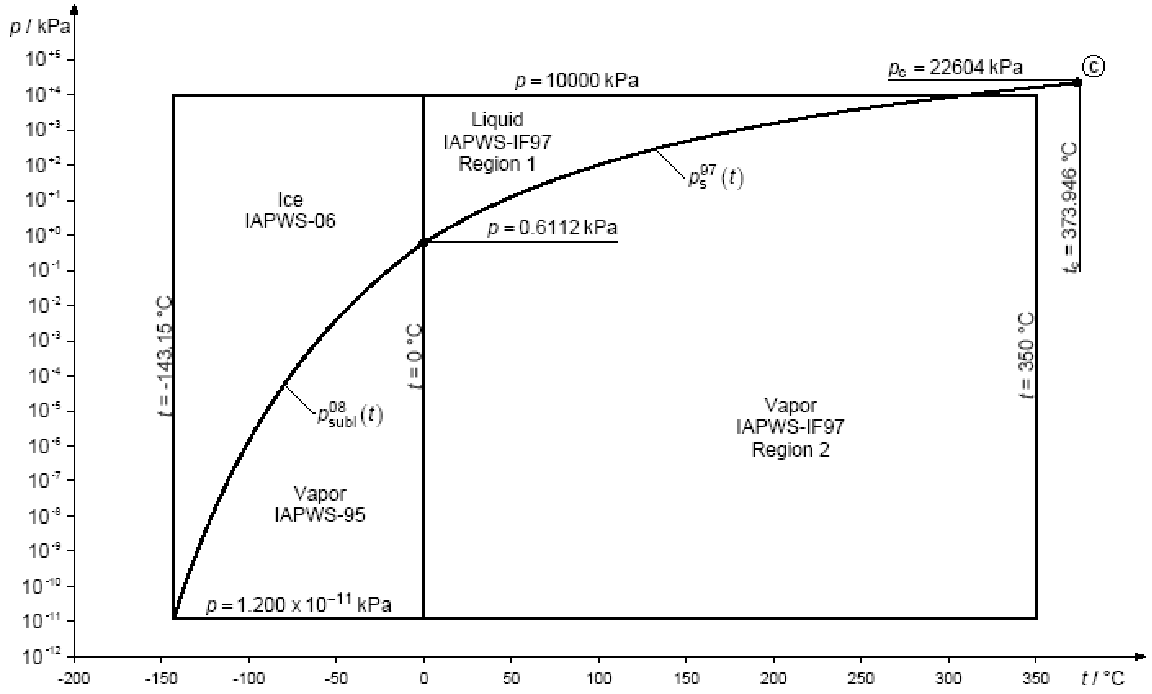


Figure 1: p-T diagram with used IAPWS formulations for steam, water, and ice.

2 Add-On FluidMAT for Mathcad for ASHRAE-LibHuAirProp-SI

2.1 Installing FluidMAT including LibHuAirProp

The FluidMAT Add-On has been developed to calculate thermodynamic properties in Mathcad® more conveniently.

Within Mathcad® it enables the direct call of functions relating to real moist air, steam, water, and ice from the ASHRAE-LibHuAirProp-SI property library.

The installation of FluidMAT and ASHRAE-LibHuAirProp_SI is described in Section 2.1 in "Part I-P Units" of this User's Guide.

2.2 Example: Calculation of *h* = f(*p*,*t*,*W*)

Now we will calculate, step by step, the air-specific enthalpy *h* as a function of pressure *p*, temperature *t* and humidity ratio *W* of moist air, using FluidMAT.

Please carry out the following steps:

- Start Mathcad®.
- Type "p:" and enter the value for pressure *p* in bar
  (Range of validity: p = 0.01 … 10 000 kPa)

  ⇒ e.g.: Enter "p:101.325", then press the tabulator button and enter "in kPa".

Note:

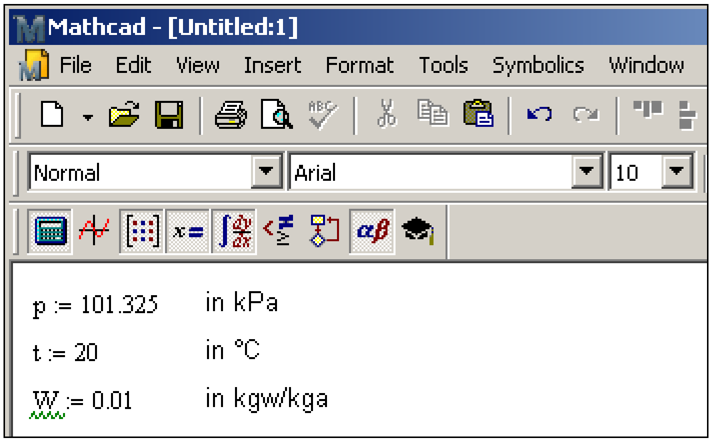
When typing in the comment containing the unit of the input parameter, Mathcad switches into the text mode, since you type in a space using the space bar, e.g. "in<space>kPa". The text modus is marked by a red cursor instead of a blue one in the math mode. After typing a comment, always finish by positioning the mouse pointer below the variable typed in before and clicking the left mouse button to switch back to math mode.

- Type "t:" and enter the value for temperature *t* in °C
  (Range of validity: t = –143.15 ... 350°C)

  ⇒ e.g.: Enter "t:20", then press the tabulator key and enter "in °C".
- Type "W:" and enter the value for the humidity ratio in kg_w/kg_a (*kg water* per *kg air*)
  (Range of validity: W = 0 … 10 kg_w/kg_a)

  ⇒ e.g.: Enter "W:0.01", then press the tabulator key and enter "in kgw/kga".

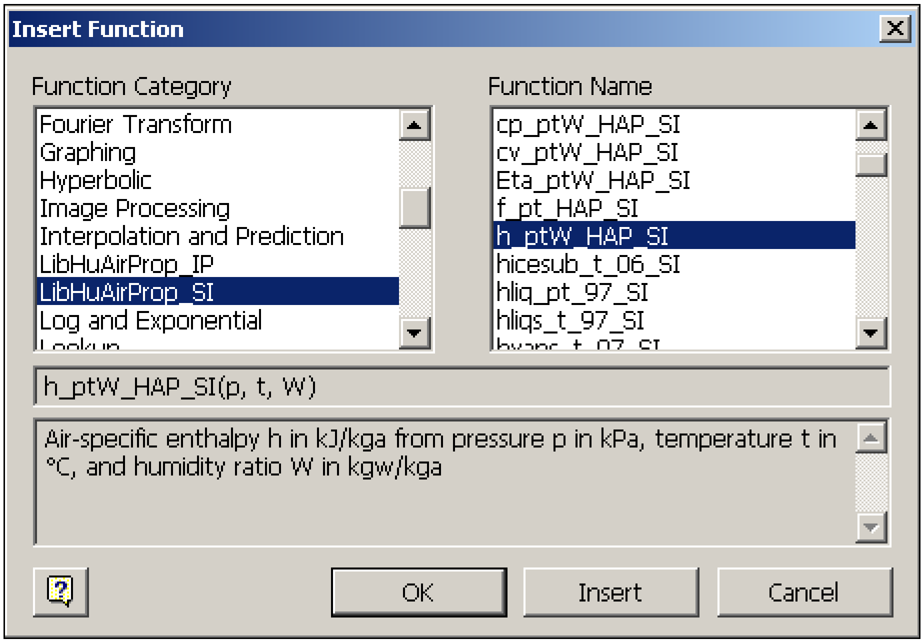
The Mathcad® sheet should now look as shown in Figure 2.2.1.



p := 101.325   in kPa
t := 20   in °C
W := 0.01   in kgw/kga

Figure 2.2.1: Example Mathcad® sheet after input of the given parameters

- Enter the symbol for the result and then a colon
  ⇒ e.g.: Type "h:" and press the Enter key
- Click "Insert" in the Mathcad® menu bar and then "Function…"
  The "Insert function" window appears (see Figure 2.1.2)
- Click "LibHuAirProp_SI" under "Function Category" on the left hand side (see Figure 2.2.2)
- Choose "h_ptW_HAP_SI" under "Function name" on the right hand side

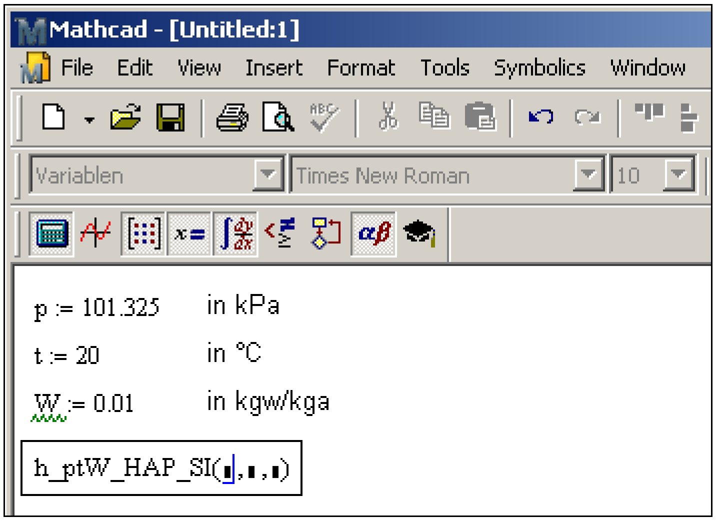


h_ptW_HAP_SI(p, t, W)

Air-specific enthalpy h in kJ/kga from pressure p in kPa, temperature t in °C, and humidity ratio W in kgw/kga

Figure 2.2.2: Choice of library and function name

- Click the "OK" button
  Now you will see the line "**h_ptW_HAP_SI(■, ■, ■)**" in the Mathcad® window (see Figure 2.2.3).



```
p := 101.325     in kPa
t := 20          in °C
W := 0.01        in kgw/kga
h_ptW_HAP_SI(▮,▮,▮)
```

Figure 2.2.3: Example Mathcad® sheet with formula and placeholders

- The cursor is now situated on the first operand. You can now enter the value for *p* either by entering the value directly or by entering the name of the variable where the value was saved.

  ⇒ e.g.: Enter "p".

- Situate the cursor on the next placeholder. You can now enter the value for the temperature *t* either by entering the value for *t* directly or by typing the name of the variable in which the value of the temperature has been saved.

  ⇒ e.g.: Enter "t".

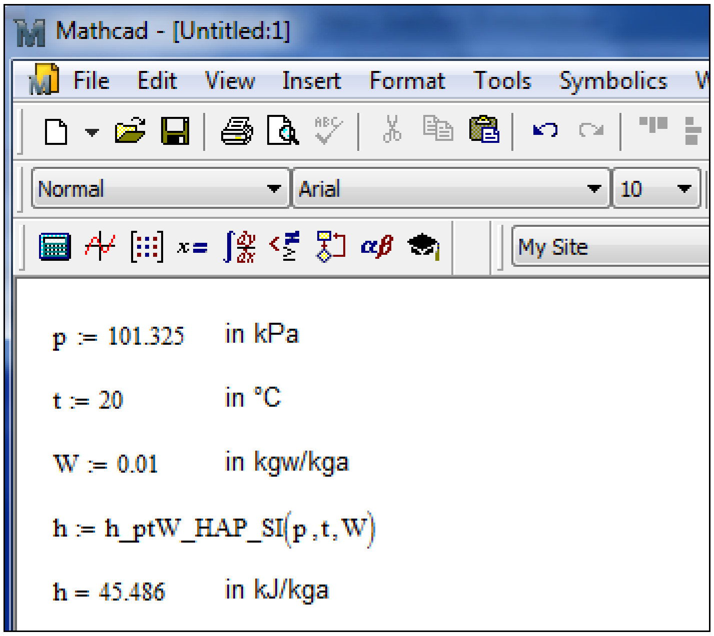
- Situate the cursor on the next placeholder. You can now enter the value for the humidity ratio *W* either by entering the value for *W* directly or by typing the name of the variable in which the value of the humidity ratio has been saved.

  ⇒ e.g.: Enter "W".

- Close the input formula by pressing the "Enter" key.
- You can now go on working with the variable *h* which we have just calculated, or you can have the result for this calculated. If you wish to see the result, type the command **"h="** on the next line in the Mathcad® window
- The result for *h* in kJ/kg$_a$ appears. To add the unit, press the tabulator button twice and enter "in kJ/kga".

  ⇒ The result in our sample calculation here is: h = 45.486 kJ/kg$_a$.

  The representation of the result depends on the number of decimal places which you have set in Mathcad.



$p := 101.325$ in kPa

$t := 20$ in °C

$W := 0.01$ in kgw/kga

$h := h\_ptW\_HAP\_SI(p,t,W)$

$h = 45.486$ in kJ/kga

Figure 2.2.4: Example Mathcad® sheet with finished calculation

The calculation of *h* = f(*p*,*t*,*W*) has been carried out.

You can now arbitrarily change the values for *p*, *t*, and *W*. The air-specific enthalpy is recalculated and updated every time you change the data. This shows that the Mathcad® data flow and the DLL calculations are working together successfully.

2.3 Removing FluidMAT including LibHuAirProp

The de-installation of FluidMAT and ASHRAE-LibHuAirProp_SI is described in Section 2.4 in "Part I-P Units" of this User's Guide.

3 Property Functions of ASHRAE-LibHuAirProp-SI

3.1 Functions for Real Moist Air

Thermal Diffusivity *a* = f(*p*,*t*,*W*)

Function Name:

a_ptW_HAP_SI

Fortran Program:

REAL*8 FUNCTION   A_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p	-	Total pressure p in kPa
t	-	Temperature t in °C
W	-	Humidity ratio W in $\mathrm{kg_w/kg_a}$

Result:

a_ptW_HAP_SI - Thermal diffusivity of humid air in $\mathrm{m^2/s}$

Range of Validity:

Temperature t:	from -73.15°C to 350°C
Total pressure p:	from 0.01 kPa to 10 000 kPa
Humidity ratio W:	$0 \le W \le W_\mathrm{s}$

Comments:

- Thermal diffusivity $a = \dfrac{\lambda}{\rho \cdot c_p}$
- Calculation for supersaturated humid air ($W > W_\mathrm{s}$) is not possible

Result for Wrong Input Values:

a_ptW_HAP_SI = -1000

References:

$\lambda(p,t,W)$	Herrmann et al. [3], [4]
$\rho(p,t,W)$	Herrmann et al. [1], [2]
$c_p(p,t,W)$	Herrmann et al. [1], [2]

Relative Pressure Coefficient α_p = f(p,t,W)

Function Name:

alphap_ptW_HAP_SI

Fortran Program:

REAL*8 FUNCTION ALPHAP_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in kPa
t - Temperature t in °C
W - Humidity ratio W in $\mathrm{kg_w/kg_a}$

Result:

alphap_ptW_HAP_SI - Relative pressure coefficient of humid air in 1/K

Range of Validity:

Temperature t:	from -143.15°C to 350°C
Total pressure p:	from 0.01 kPa to 10 000 kPa
Humidity ratio W:	$0 \le W \le W_\mathrm{s}$

Comments:

- Relative pressure coefficient $\alpha_p = \frac{1}{p}\left(\frac{\partial p}{\partial T}\right)_\mathrm{v}$
- Calculation for supersaturated humid air ($W > W_\mathrm{s}$) is not possible

Result for Wrong Input Values:

alphap_ptW_HAP_SI = -1000

References:

$\rho(p,t,W)$ Herrmann et al. [1], [2]

Isothermal Stress Coefficient β_p = f(p,t,W)

Function Name:

betap_ptW_HAP_SI

Fortran Program:

REAL*8 FUNCTION BETAP_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in kPa
t - Temperature t in °C
W - Humidity ratio W in $\mathrm{kg_w/kg_a}$

Result:

betap_ptW_HAP_SI - Isothermal stress coefficient of humid air in $\mathrm{kg/m^3}$

Range of Validity:

Temperature t:	from -143.15°C to 350°C
Total pressure p:	from 0.01 kPa to 10 000 kPa
Humidity ratio W:	$0 \le W \le W_\mathrm{s}$

Comments:

- Isothermal stress coefficient $\beta_p = -\dfrac{1}{p}\left(\dfrac{\partial p}{\partial v}\right)_\mathrm{T}$
- Calculation for supersaturated humid air ($W > W_\mathrm{s}$) is not possible

Result for Wrong Input Values:

betap_ptW_HAP_SI = -1000

References:

$v(p,t,W)$ Herrmann et al. [1], [2]

Speed of Sound *c* = f(*p*,*t*,*W*)

Function Name:

c_ptW_HAP_SI

Fortran Program:

REAL*8 FUNCTION C_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in kPa

t - Temperature t in °C

W - Humidity ratio W in $\mathrm{kg_w/kg_a}$

Result:

c_ptW_HAP_SI - Speed of sound of humid air in m/s

Range of Validity:

Temperature *t*: from -143.15°C to 350°C

Total pressure *p*: from 0.01 kPa to 10 000 kPa

Humidity ratio *W*: $0 \le W \le 10\,\mathrm{kg_w/kg_a}$

Comments:

- Speed of sound $c = v\sqrt{-\left(\frac{\partial p}{\partial v}\right)_s}$
- When calculating supersaturated air an ideal mixing model (saturated humid air and water droplets (or ice crystals) homogeneously mixed) is applied

Result for Wrong Input Values:

c_ptW_HAP_SI = -1000

References:

$v(p,t,W)$ Herrmann et al. [1], [2]

Specific Isobaric Heat Capacity c_p = f(p,t,W)

Function Name:

cp_ptW_HAP_SI

Fortran Program:

REAL*8 FUNCTION   CP_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p	-	Total pressure *p* in kPa
t	-	Temperature *t* in °C
W	-	Humidity ratio *W* in kg_w/kg_a

Result:

cp_ptW_HAP_SI - Specific isobaric heat capacity of humid air in kJ/(kg K)

Range of Validity:

Temperature *t*:	from -143.15°C to 350°C
Total pressure *p*:	from 0.01 kPa to 10 000 kPa
Humidity ratio *W*:	$0 \le W \le W_s$

Comments:

- Specific isobaric heat capacity $c_p = \left(\frac{\partial h}{\partial T}\right)_p$
- Calculation for supersaturated humid air ($W > W_s$) is not possible

Result for Wrong Input Values:

cp_ptW_HAP_SI = -1000

References:

$h(p,t,W)$ Herrmann et al. [1], [2]

Specific Isochoric Heat Capacity c_v = f(p,t,W)

Function Name:

cv_ptW_HAP_SI

Fortran Program:

```
REAL*8 FUNCTION   CV_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W
```

Input Values:

p - Total pressure *p* in kPa
t - Temperature *t* in °C
W - Humidity ratio *W* in kg_w/kg_a

Result:

cv_ptW_HAP_SI - Specific isochoric heat capacity of humid air in kJ/(kg K)

Range of Validity:

Temperature *t*:	from -143.15°C to 350°C
Total pressure *p*:	from 0.01 kPa to 10 000 kPa
Humidity ratio *W*:	$0 \le W \le W_s$

Comments:

- Specific isochoric heat capacity $c_v = \left(\frac{\partial u}{\partial T}\right)_v$

- Calculation for supersaturated humid air ($W > W_s$) is not possible

Result for Wrong Input Values:

cv_ptW_HAP_SI = -1000

References:

$c_v(p,t,W)$ Herrmann et al. [3], [4]

Enhancement Factor *f* = f(*p*,*t*)

Function Name:

f_pt_HAP_SI

Fortran Program:

```
REAL*8 FUNCTION   F_PT_HUAIRPROP(P,T), REAL*8 P,T
```

Input Values:

p - Total pressure p in kPa
t - Temperature t in °C

Result:

f_pt_HAP_SI - Enhancement factor of water (decimal ratio)

Range of Validity:

Temperature t:	from -143.15°C to 350°C
Total pressure p:	from 0.01 kPa to 10 000 kPa

Comments:

- Enhancement factor $f = \dfrac{p_{\mathrm{H2O,s}}}{p_{\mathrm{s}}(t)}$

with $p_{\mathrm{s}}(t)$ for $t \geq 0.01$°C - Steam pressure of water

for $t < 0.01$°C - Sublimation pressure of water

- Describes the enhancement of the saturation pressure of water in the air atmosphere under elevated pressure
- Derived iteratively from the isothermal compressibility of liquid water, from Henry's constant [15], [16] and from the virial coefficients of air, water, and the air-water mixture

Result for Wrong Input Values:

f_pt_HAP_SI = -1000

References:

$f(p,t)$	Herrmann et al. [1], [2]

Air-Specific Enthalpy *h* = f(*p*,*t*,*W*)

Function Name:

h_ptW_HAP_SI

Fortran Program:

REAL*8 FUNCTION H_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in kPa

t - Temperature t in °C

W - Humidity ratio W in kg_w/kg_a

Result:

h_ptW_HAP_SI - Air-specific enthalpy in kJ/kg_a

Range of Validity:

Temperature t:	from -143.5°C to 350°C
Total pressure p:	from 0.01 kPa to 10 000 kPa
Humidity ratio W:	$0 \le W \le 10\, kg_w/kg_a$

Comments:

- When calculating supersaturated air an ideal mixing model (saturated humid air and water droplets (or ice crystals) homogeneously mixed) is applied

Result for Wrong Input Values:

h_ptW_HAP_SI = -1000

References:

$h(p,t,W)$	Herrmann et al. [1], [2]
$h_w(p,t)$	IAPWS-IF97 [7], [8] and IAPWS-06 [11]
$h_a(t)$	Lemmon et al. [14]

Dynamic Viscosity η = f(p,t,W)

Function Name:

Eta_ptW_HAP_SI

Fortran Program:

REAL*8 FUNCTION ETA_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in kPa
t - Temperature t in °C
W - Humidity ratio W in $\mathrm{kg_w/kg_a}$

Result:

Eta_ptW_HAP_SI - Dynamic viscosity of humid air in Pa s

Range of Validity:

Temperature t:	from -73.15°C to 350°C
Total pressure p:	from 0.01 kPa to 10 000 kPa
Humidity ratio W:	$0 \le W \le 10\,\mathrm{kg_w/kg_a}$

Comments:

- A new very accurate algorithm is implemented between 0°C and 350°C
- When calculating supersaturated air an ideal mixing model (saturated humid air and water droplets (or ice crystals) homogeneously mixed) is applied

Result for Wrong Input Values:

Eta_ptW_HAP_SI = -1000

References:

$\eta(p,t,W)$	Herrmann et al. [3], [4]
$\eta_a(t)$	Lemmon et al. [18]
$\eta_w(p,t)$	IAPWS-IF97 [7], [8] and IAPWS-08 [19]

Isentropic Exponent $\kappa = \mathrm{f}(p,t,W)$

Function Name:

Kappa_ptW_HAP_SI

Fortran Program:

REAL*8 FUNCTION   KAPPA_PTW_HUAIRPROP(P,T, W), REAL*8 P,T,W

Input Values:

p - Total pressure p in kPa

t - Temperature t in °C

W - Humidity ratio W in $\mathrm{kg_w/kg_a}$

Result:

Kappa_ptW_HAP_SI - Isentropic exponent

Range of Validity:

Temperature t:	from -143.5°C to 350°C
Total pressure p:	from 0.01 kPa to 10 000 kPa
Humidity ratio W:	$0 \le W \le 10\,\mathrm{kg_w/kg_a}$

Comments:

- Isentropic exponent $\kappa = -\frac{v}{p}\left(\frac{\partial p}{\partial v}\right)_s$
- When calculating supersaturated air an ideal mixing model (saturated humid air and water droplets homogeneously mixed) is applied for $t \geq 0.01$°C. For temperatures below (ice fog) the value of the saturated state is applied.

Result for Wrong Input Values:

Kappa_ptW_HAP_SI = -1000

References:

$v(p,t,W)$ Herrmann et al. [1], [2]

Thermal Conductivity $\lambda = \mathrm{f}(p,t,W)$

Function Name:

Lambda_ptW_HAP_SI

Fortran Program:

REAL*8 FUNCTION LAMBDA_PTW_HUAIRPROP(P,T, W), REAL*8 P,T,W

Input Values:

p - Total pressure p in kPa
t - Temperature t in °C
W - Humidity ratio W in $\mathrm{kg_w/kg_a}$

Result:

Lambda_ptW_HAP_SI - Thermal conductivity in W/(m K)

Range of Validity:

Temperature t:	from -73.5°C to 350°C
Total pressure p:	from 0.01 kPa to 10 000 kPa
Humidity ratio W:	$0 \leq W \leq 10\,\mathrm{kg_w/kg_a}$

Comments:

- A new very accurate algorithm is implemented between 0°C and 350°C
- When calculating supersaturated air an ideal mixing model (saturated humid air and water droplets (or ice crystals) homogeneously mixed) is applied

Result for Wrong Input Values:

Lambda_ptW_HAP_SI = -1000

References:

$\lambda(p,t,W)$	Herrmann et al. [3], [4]
$\lambda_\mathrm{a}(t)$	Lemmon et al. [18]
$\lambda_\mathrm{w}(p,t)$	IAPWS-IF97 [7], [8] and IAPWS-08 [20]

Kinematic Viscosity ν = f(p,t,W)

Function Name:

Ny_ptW_HAP_SI

Fortran Program:

REAL*8 FUNCTION   NY_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in kPa
t - Temperature t in °C
W - Humidity ratio W in $\mathrm{kg_w/kg_a}$

Result:

Ny_ptW_HAP_SI - Kinematic viscosity in $\mathrm{m^2/s}$

Range of Validity:

Temperature t:	from -73.5°C to 350°C
Total pressure p:	from 0.01 kPa to 10 000 kPa
Humidity ratio W:	$0 \le W \le W_s$

Comments:

- Kinematic Viscosity $\nu = \dfrac{\eta}{\rho}$

Result for Wrong Input Values:

Ny_ptW_HAP_SI = -1000

References:

$\eta(p,t,W)$	Herrmann et al. [3], [4]
$\rho(p,t,W)$	Herrmann et al. [1], [2]

Backward Function: Total Pressure p = f(t,s,W)

Function Name:

p_tsW_HAP_SI

Fortran Program:

REAL*8 FUNCTION P_TSW_HUAIRPROP(T,S,W), REAL*8 T,S,W

Input Values:

t - Temperature t in °C

s - Air-specific entropy s in kJ/(kg$_a$ K)

W - Humidity ratio W in kg$_w$/kg$_a$

Result:

p_tsW_HAP_SI - Total pressure in kPa

Range of Validity:

Temperature t:	from -143.5°C to 350°C
Air-specific entropy s:	from -26.53 kJ/(kg$_a$ K) to 38.990 kJ/(kg$_a$ K)
Humidity ratio W:	$0 \le W \le 10\,\mathrm{kg_w/kg_a}$

Comments:

- Iteration of total pressure p from s = f(p,t,W)

Result for Wrong Input Values:

p_tsW_HAP_SI = -1000

References:

$s(p,t,W)$ Herrmann et al. [1], [2]

Pressure p = f(z_{ele})

Function Name:

p_zele_HAP_SI

Fortran Program:

REAL*8 FUNCTION   P_ZELE_HUAIRPROP(ZELE), REAL*8 ZELE

Input Values:

z_{ele} - Elevation z_{ele} in m

Result:

p_zele_HAP_SI - Pressure of humid air in kPa

Range of Validity:

Elevation z_{ele}	from -5,000 m to 11,000 m

Comments:

- Pressure of humid air from elevation
- $p(z_{\mathrm{ele}}) = 101.325\,\mathrm{kPa} \cdot \left(1 - 2.25577 \cdot 10^{-5} \cdot \dfrac{z_{\mathrm{ele}}}{\mathrm{m}}\right)^{5.256}$

Result for Wrong Input Values:

p_zele_HAP_SI = -1000

References:

$p(z_{\mathrm{ele}})$	ASHRAE [23]

Partial Pressure of Dry Air p_{Air} = f(p, t, W)

Function Name:

pAir_ptW_HAP_SI

Fortran Program:

REAL*8 FUNCTION PAIR_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in kPa
t - Temperature t in °C
W - Humidity ratio W in $\mathrm{kg_w/kg_a}$

Result:

pAir_ptW_HAP_SI - Partial pressure of (dry) air in humid air in kPa

Range of Validity:

Temperature t:	from -143.15°C to 350°C
Total pressure p:	from 0.01 kPa to 10 000 kPa
Humidity ratio W:	$0 \le W \le 10\,\mathrm{kg_w/kg_a}$

Comments:

- Partial pressure of (dry) air in humid air $p_{Air} = 1 - p_{H2O}$
- Partial pressure of water vapor at saturation is calculated in case of supersaturated humid air ($W > W_s(p,t)$)
- The temperature value is used to calculate the saturation state

Result for Wrong Input Values:

pAir_ptW_HAP_SI = -1000

References:

$p_{H2O}(p,W)$ Herrmann et al. [1], [2]

Partial Pressure of Water Vapor p_{H2O} = f(p,t,W)

Function Name:

pH2O_ptW_HAP_SI

Fortran Program:

REAL*8 FUNCTION PH2O_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p	-	Total pressure p in kPa
t	-	Temperature t in °C
W	-	Humidity ratio W in $\mathrm{kg_w/kg_a}$

Result:

pH2O_ptW_HAP_SI - Partial pressure of water vapor in humid air in kPa

Range of Validity:

Temperature t:	from -143.15°C to 350°C
Total pressure p:	from 0.01 kPa to 10 000 kPa
Humidity ratio W:	$0 \le W \le 10\,\mathrm{kg_w/kg_a}$

Comments:

- Partial pressure of water vapor in humid air $p_{H2O} = \dfrac{W \cdot p}{\left(\dfrac{R_a}{R_w} + W\right)}$
- Partial pressure of water vapor at saturation is calculated in case of supersaturated humid air ($W > W_s(p,t)$)
- The temperature value is used to calculate the saturation state

Result for Wrong Input Values:

pH2O_ptW_HAP_SI = -1000

References:

$p_{H2O}(p,W)$ Herrmann et al. [1], [2]

Partial Saturation Pressure of Water Vapor $p_{H2O,s}$ = f(p, t)

Function Name:

pH2Os_pt_HAP_SI

Fortran Program:

```
REAL*8 FUNCTION   PH2OS_PT_HUAIRPROP(P,T), REAL*8 P,T
```

Input Values:

p - Total pressure p in kPa

t - Temperature t in °C

Result:

pH2Os_pt_HAP_SI - Partial saturation pressure of water vapor in humid air in kPa

Range of Validity:

Temperature t:	from -143.15°C to 350°C
Total pressure p:	from 0.01 kPa to 10 000 kPa

Comments:

- Partial pressure of steam at saturation $p_{H2O,s} = f \cdot p_s(t)$
  with $p_s(t)$ for $t \geq 0.01$°C - Steam pressure of water
  for $t < 0.01$°C - Sublimation pressure of water

Result for Wrong Input Values:

pH2Os_pt_HAP_SI = -1000

References:

$f(p,t)$		Herrmann et al. [1], [2]
$p_s(t)$	for $t \geq 0.01$°C	IAPWS-IF97 [7], [8]
	for $t < 0.01$°C	IAPWS-08 [11]

Relative Humidity φ = f(p,t,W)

Function Name:

phi_ptW_HAP_SI

Fortran Program:

```
REAL*8 FUNCTION   PHI_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W
```

Input Values:

p - Total pressure p in kPa
t - Temperature t in °C
W - Humidity ratio W in $\mathrm{kg_w/kg_a}$

Result:

phi_ptW_HAP_SI - Relative humidity (decimal ratio)

Range of Validity:

Temperature t:	from -143.15°C to 350°C
Total pressure p:	from 0.01 kPa to 10 000 kPa
Humidity ratio W:	$0 \le W \le 10\,\mathrm{kg_w/kg_a}$

Comments:

- Relative humidity $\varphi = \dfrac{p_{\mathrm{H2O}}}{p_{\mathrm{H2O,s}}}$
- This equation is valid for $p_{\mathrm{H2O}} \le p_{\mathrm{H2O,s}}$ and for $0 \le \varphi \le 1$

Result for Wrong Input Values:

phi_ptW_HAP_SI = -1000

References:

$\varphi(p,t,W)$ Herrmann et al. [1], [2]

Prandtl Number *Pr* = f(*p*,*t*,*W*)

Function Name:

Pr_ptW_HAP_SI

Fortran Program:

REAL*8 FUNCTION PR_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in kPa
t - Temperature t in °C
W - Humidity ratio W in $\mathrm{kg_w/kg_a}$

Result:

Pr_ptW_HAP_SI - Prandtl number

Range of Validity:

Temperature t:	from -73.5°C to 350°C
Total pressure p:	from 0.01 kPa to 10 000 kPa
Humidity ratio W:	$0 \le W \le 10\,\mathrm{kg_w/kg_a}$

Comments:

- Prandtl number $Pr = \dfrac{\eta \cdot c_p}{\lambda}$
- Calculation for supersaturated humid air ($W > W_s$) is not possible

Result for Wrong Input Values:

Pr_ptW_HAP_SI = -1000

References:

$\eta(p,t,W)$	Herrmann et al. [3], [4]
$c_p(p,t,W)$	Herrmann et al. [3], [4]
$\lambda(p,t,W)$	Lemmon et al. [20]

Mole Fraction of Dry Air ψ_{Air} = f(W)

Function Name:

PsiAir_W_HAP_SI

Fortran Program:

REAL*8 FUNCTION PSIAIR_W_HUAIRPROP(W), REAL*8 W

Input Values:

W - Humidity ratio W in $\mathrm{kg_w/kg_a}$

Result:

PsiAir_W_HAP_SI - Mole fraction of (dry) air in humid air in $\mathrm{mol_a/mol}$

Range of Validity:

Humidity ratio W: $0 \le W \le 10\,\mathrm{kg_w/kg_a}$

Comments:

- Mole fraction of air $\psi_{\mathrm{Air}} = 1 - \psi_{\mathrm{H2O}} = 1 - \left(\dfrac{W}{\dfrac{R_{\mathrm{a}}}{R_{\mathrm{H2O}}} + W} \right)$

Result for Wrong Input Values:

PsiAir_W_HAP_SI = -1000

References:

$\psi_{\mathrm{Air}}(W)$ Herrmann et al. [1], [2]

Mole Fraction of Water $\psi_{\mathrm{H2O}} = \mathrm{f}(W)$

Function Name:

PsiH2O_W_HAP_SI

Fortran Program:

REAL*8 FUNCTION PSIH2O_W_HUAIRPROP(W), REAL*8 W

Input Values:

W - Humidity ratio W in $\mathrm{kg_w/kg_a}$

Result:

PsiH2O_W_HAP_SI - Mole fraction of water in humid air in $\mathrm{mol_w/mol}$

Range of Validity:

Humidity ratio W: $0 \le W \le 10\,\mathrm{kg_w/kg_a}$

Comments:

- Mole fraction of water $\psi_{\mathrm{H2O}} = \dfrac{W}{\dfrac{R_\mathrm{a}}{\mathrm{R_{H2O}}} + W}$

Result for Wrong Input Values:

PsiH2O_W_HAP_SI = -1000

References:

$\psi_{\mathrm{H2O}}(W)$ Herrmann et al. [1], [2]

Density ρ = f(p,t,W)

Function Name:

Rho_ptW_HAP_SI

Fortran Program:

REAL*8 FUNCTION RHO_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in kPa
t - Temperature t in °C
W - Humidity ratio W in $\mathrm{kg_w/kg_a}$

Result:

Rho_ptW_HAP_SI - Density of humid air in $\mathrm{kg/m^3}$

Range of Validity:

Temperature t:	from -143.15°C to 350°C
Total pressure p:	from 0.01 kPa to 10 000 kPa
Humidity ratio W:	$0 \le W \le 10\,\mathrm{kg_w/kg_a}$

Comments:

- Density of humid air obtained from air-specific volume: $\rho = \dfrac{1+W}{v}$

Result for Wrong Input Values:

Rho_ptW_HAP_SI = -1000

References:

$\rho(p,t,W)$ Herrmann et al. [1], [2]

Air-Specific Entropy s = f(p,t,W)

Function Name:

s_ptW_HAP_SI

Fortran Program:

REAL*8 FUNCTION   S_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in kPa
t - Temperature t in °C
W - Humidity ratio W in $\mathrm{kg_w/kg_a}$

Result:

s_ptW_HAP_SI - Air-specific entropy in $\mathrm{kJ/(kg_a\,K)}$

Range of Validity:

Temperature t:	from -143.15°C to 350°C
Total pressure p:	from 0.01 kPa to 10 000 kPa
Humidity ratio W:	$0 \le W \le 10\,\mathrm{kg_w/kg_a}$

Comments:

- When calculating supersaturated air an ideal mixing model (saturated humid air and water droplets (or ice crystals) homogeneously mixed) is applied

Result for Wrong Input Values:

s_ptW_HAP_SI = -1000

References:

$s(p,t,W)$ Herrmann et al. [1], [2]

Backward Function: Temperature *t* = f(*p*,*h*,*φ*)

Function Name:

t_phphi_HAP_SI

Fortran Program:

REAL*8 FUNCTION T_PHPHI_HUAIRPROP(P,H,PHI), REAL*8 P,H,PHI

Input Values:

p - Total pressure p in kPa
h - Air-specific enthalpy h in kJ/kg$_a$
φ - Relative humidity φ (decimal ratio)

Result:

t_phphi_HAP_SI - Temperature from pressure, enthalpy, and relative humidity in °C

Range of Validity:

Total pressure p:	from 0.01 kPa to 10 000 kPa
Air-specific enthalpy h:	from -5745 kJ/kg$_a$ to 29690 kJ/kg$_a$
Relative humidity φ:	$0 \le \varphi \le 1$

Comments:

- Iteration of temperature t from h = f(p,t,W) using W = f(p,t,φ)

Result for Wrong Input Values:

t_phphi_HAP_SI = -1000

References:

$h(p,t,W)$ Herrmann et al. [1], [2]

Backward Function: Temperature *t* = f(*p*,*h*,*W*)

Function Name:

t_phW_HAP_SI

Fortran Program:

REAL*8 FUNCTION   T_PHW_HUAIRPROP(P,H,W), REAL*8 P,H,W

Input Values:

p	-	Total pressure *p* in kPa
h	-	Air-specific enthalpy *h* in kJ/kg_a
W	-	Humidity ratio *W* in kg_w/kg_a

Result:

t_phW_HAP_SI - Temperature from pressure, enthalpy, and humidity ratio in °C

Range of Validity:

Total pressure *p*:	from 0.01 kPa to 10 000 kPa
Air-specific enthalpy *h*:	from -5745 kJ/kg_a to 29690 kJ/kg_a
Humidity ratio *W*:	$0 \le W \le 10\,kg_w/kg_a$

Comments:

- Iteration of temperature *t* from *h* = f(*p*,*t*,*W*)

Result for Wrong Input Values:

t_phW_HAP_SI = -1000

References:

$h(p,t,W)$ Herrmann et al. [1], [2]

Backward Function: Temperature *t* = f(*p*,*s*,*W*)

Function Name:

t_psW_HAP_SI

Fortran Program:

REAL*8 FUNCTION T_PSW_HUAIRPROP(P,S,W), REAL*8 P,S,W

Input Values:

p	-	Total pressure p in kPa
s	-	Air-specific entropy s in kJ/(kg$_a$ K)
W	-	Humidity ratio W in kg$_w$/kg$_a$

Result:

t_psW_HAP_SI - Temperature from pressure, entropy, and humidity ratio in °C

Range of Validity:

Total pressure p:	from 0.01 kPa to 10 000 kPa
Air-specific entropy s:	from -26.53 kJ/(kg$_a$ K) to 38.990 kJ/(kg$_a$ K)
Humidity ratio W:	$0 \le W \le 10\,\text{kg}_w/\text{kg}_a$

Comments:

- Iteration of temperature t from s = f(p,t,W)

Result for Wrong Input Values:

t_psW_HAP_SI = -1000

References:

$s(p,t,W)$ Herrmann et al. [1], [2]

Backward Function: Temperature $t = \mathrm{f}(p, t_{\mathrm{wb}}, W)$

Function Name:

t_ptwbW_HAP_SI

Fortran Program:

REAL*8 FUNCTION T_PTWBW_HUAIRPROP(P,TWB,W), REAL*8 P,TWB,W

Input Values:

p - Total pressure p in kPa
t_{wb} - Wet-bulb temperature in °C
W - Humidity ratio W in $\mathrm{kg_w/kg_a}$

Result:

t_ptwbW_HAP_SI - Temperature from pressure, wet bulb temperature and humidity ratio in °C

Range of Validity:

Total pressure p:	from 0.01 kPa to 10 000 kPa
Wet bulb temperature t_{wb}:	from -143.15°C to 350°C
Humidity ratio W:	$0 \le W \le 10\,\mathrm{kg_w/kg_a}$

Comments:

- Iterationof temperature t from $t_{\mathrm{wb}} = \mathrm{f}(p,t,W)$

Result for Wrong Input Values:

t_ptwbW_HAP_SI = -1000

References:

$t_{\mathrm{wb}}(p,t,W)$ Herrmann et al. [1], [2]

Dew-Point/Frost-Point Temperature t_d = f(p,W)

Function Name:

td_pW_HAP_SI

Fortran Program:

REAL*8 FUNCTION TD_PW_HUAIRPROP(P,W), REAL*8 P,W

Input Values:

p	-	Total pressure p in kPa
W	-	Humidity ratio W in kg_w/kg_a

Result:

td_pW_HAP_SI - Dew-point/frost-point temperature in °C

Range of Validity:

Total pressure p:	from 0.01 kPa to 10 000 kPa
Humidity ratio W:	$0 \le W \le 10\,kg_w/kg_a$

Comments:

Dew-point temperature $t_d = t_s(p_{H2O})$ for $t \ge 0.01°C$ (saturation temperature of water in humid air)

$t_d = t_{sub}(p_{H2O})$ for $t \le 0.01°C$ (sublimation temperature of water in humid air)

Result for Wrong Input Values:

td_pW_HAP_SI = -1000

References:

$t_s(p_{H2O})$	for $t_d \ge 0.01°C$	IAPWS-IF97 [7], [8]
$t_{sub}(p_{H2O})$	for $t_d \le 0.01°C$	IAPWS-08 [11]
p_{H2O}		Herrmann et. al. [1], [2]

Saturation Temperature t_s = f(p, p_{H2O})

Function Name:

ts_ppH2O_HAP_SI

Fortran Program:

```
REAL*8 FUNCTION   TS_PPH2O_HUAIRPROP(P,PH2O), REAL*8 P,PH2O
```

Input Values:

p - Total pressure p in kPa

p_{H2O} - Partial pressure of water vapor p_{H2O} in kPa

Result:

ts_ppH2O_HAP_SI - Saturation temperature in °C

Range of Validity:

Total pressure p:	from 0.01 kPa to 10 000 kPa
Partial Pressure p_{H2O} :	from 0.01 kPa to 10 000 kPa

Comments:

- Iteration of saturation temperature t_s from $p_{H2O,s} = f(p, t)$

Result for Wrong Input Values:

ts_ppH2O_HAP_SI = -1000

References:

$p_{H2O,s}$ Herrmann et. al. [1], [2]

Wet-Bulb/Ice-Bulb Temperature t_{wb} = f(p,t,W)

Function Name:

twb_ptW_HAP_SI

Fortran Program:

REAL*8 FUNCTION TWB_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in kPa

t - Temperature t in °C

W - Humidity ratio W in kg_w/kg_a

Result:

twb_ptW_HAP_SI - Wet-bulb/ice-bulb temperature in °C

Range of Validity:

Temperature t:	from -143.15°C to 350°C
Total pressure p:	from 0.01 kPa to 10 000 kPa
Humidity ratio W:	$0 \le W \le 10\,\text{kg}_w/\text{kg}_a$

Comments:

- Iteration of wet-bulb/ice-bulb temperature t_{wb} from $h^{\text{unsaturated}}(p,t,W) = h^{\text{fog}}(p,t_{wb},W)$
- Calculation for supersaturated humid air ($W > W_s$) is not possible

Result for Wrong Input Values:

twb_ptW_HAP_SI = -1000

References:

$t_{wb}(p,t,W)$ Herrmann et al. [1], [2]

Air-Specific Internal Energy *u* = f(*p*,*t*,*W*)

Function Name:

u_ptW_HAP_SI

Fortran Program:

REAL*8 FUNCTION U_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in kPa
t - Temperature t in °C
W - Humidity ratio W in $\mathrm{kg_w/kg_a}$

Result:

u_ptW_HAP_SI - Air-specific internal energy in $\mathrm{kJ/kg_a}$

Range of Validity:

Temperature *t*:	from -143.15°C to 350°C
Total pressure *p*:	from 0.01 kPa to 10 000 kPa
Humidity ratio *W*:	$0 \le W \le 10\,\mathrm{kg_w/kg_a}$

Comments:

- Internal energy $u = h - pv$

Result for Wrong Input Values:

u_ptW_HAP_SI = -1000

References:

$u(p,t,W)$ Herrmann et al. [1], [2]

Air-Specific Volume *v* = f(*p*,*t*,*W*)

Function Name:

v_ptW_HAP_SI

Fortran Program:

REAL*8 FUNCTION V_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in kPa

t - Temperature t in °C

W - Humidity ratio W in kg_w/kg_a

Result:

v_ptW_HAP_SI - Air-specific volume in m^3/kg_a

Range of Validity:

Temperature *t*:	from -143.15°C to 350°C
Total pressure *p*:	from 0.01 kPa to 10 000 kPa
Humidity ratio *W*:	$0 \le W \le 10\,kg_w/kg_a$

Comments:

- When calculating supersaturated air an ideal mixing model (saturated humid air and water droplets (or ice crystals) homogeneously mixed) is applied

Result for Wrong Input Values:

v_ptW_HAP_SI = -1000

References:

$v(p,t,W)$ Herrmann et al. [1], [2]

Humidity Ratio from Partial Pressure of Steam $W = f(p,t,p_{H2O})$

Function Name:

W_ptpH2O_HAP_SI

Fortran Program:

REAL*8 FUNCTION W_PTPH2O_HUAIRPROP(P,T,PH2O), REAL*8 P,T,PH2O

Input Values:

p - Total pressure p in kPa
t - Temperature t in °C
p_{H2O} - Partial pressure of water p_{H2O} in kPa

Result:

W_ptpH2O_HAP_SI - Humidity ratio from temperature and partial pressure of water vapor in kg_w/kg_a

Range of Validity:

Total pressure p:	from 0.01 kPa to 10 000 kPa
Temperature t :	from -143.15°C to 350°C
Partial pressure p_{H2O} :	from 0.01 kPa to 10 000 kPa

Comments:

- Iteration of humidity ratio W from $p_{H2O} = f(p,t,W)$
- Result for supersaturated humid air is W_s

Result for Wrong Input Values:

W_ptpH2O_HAP_SI = -1000

References:

$p_{H2O}(p,t,W)$ Herrmann et al. [1], [2]

Humidity Ratio from Relative Humidity $W = f(p,t,\varphi)$

Function Name:

W_ptphi_HAP_SI

Fortran Program:

REAL*8 FUNCTION   W_PTPHI_HUAIRPROP(P,T,PHI), REAL*8 P,T,PHI

Input Values:

p - Total pressure p in kPa
t - Temperature t in °C
φ - Relative humidity (decimal ratio)

Result:

W_ptphi_HAP_SI - Humidity ratio from temperature and relative humidity in kg_w/kg_a

Range of Validity:

Temperature t:	from -143.15°C to 350°C
Total pressure p:	from 0.01 kPa to 10 000 kPa
Relative humidity φ:	$0 \le \varphi \le 1$

Comments:

- Iteration of humidity ratio W from $\varphi = f(p,t,W)$

Result for Wrong Input Values:

W_ptphi_HAP_SI = -1000

References:

$\varphi(p,t,W)$ Herrmann et al. [1], [2]

Humidity Ratio from Dew-Point Temperature $W = f(p,t_d)$

Function Name:

W_ptd_HAP_SI

Fortran Program:

REAL*8 FUNCTION W_PTD_HUAIRPROP(P,TD), REAL*8 P,TD

Input Values:

p - Total pressure p in kPa
t_d - Dew-point temperature t_d in °C

Result:

W_ptd_HAP_SI - Humidity ratio from temperature and dew-point temperature in kg_w/kg_a

Range of Validity:

Dew point temperature t_d:	from -143.15°C to 350°C
Total pressure p:	from 0.01 kPa to 10 000 kPa

Comments:

- Iteration of humidity ratio W from $t_d = f(p,W)$

Result for Wrong Input Values:

W_ptd_HAP_SI = -1000

References:

$t_d(p,W)$ Herrmann et al. [1], [2]

Humidity Ratio from Wet-Bulb Temperature $W = f(p, t, t_{wb})$

Function Name:

W_pttwb_HAP_SI

Fortran Program:

REAL*8 FUNCTION W_PTTWB_HUAIRPROP(P,T,TWB), REAL*8 P,T,TWB

Input Values:

p - Total pressure p in kPa
t - Temperature t in °C
t_{wb} - Wet-bulb temperature in °C

Result:

W_pttwb_HAP_SI - Humidity ratio from temperature and wet-bulb temperature in kg_w/kg_a

Range of Validity:

Total pressure p:	from 0.01 kPa to 10 000 kPa
Temperature t:	from -143.15°C to 350°C
Wet-bulb temperature t_{wb}:	from -143.15°C to 350°C

Comments:

- Iteration of humidity ratio W from $t_{wb} = f(p, t, W)$
- Calculation for supersaturated humid air ($W > W_s$) is not possible

Result for Wrong Input Values:

W_pttwb_HAP_SI = -1000

References:

$t_{wb}(p, t, W)$ Herrmann et al. [1], [2]

Saturation Humidity Ratio W_s = f(p,t)

Function Name:

Ws_pt_HAP_SI

Fortran Program:

REAL*8 FUNCTION   WS_PT_HUAIRPROP(P,T), REAL*8 P,T

Input Values:

p	-	Total pressure *p* in kPa
t	-	Temperature *t* in °C

Result:

Ws_pt_HAP_SI - Saturation humidity ratio (mass fraction) in kg_w/kg_a

Range of Validity:

Total pressure *p*:	from 0.01 kPa to 10 000 kPa
Temperature *t*:	from -143.15°C to 350°C

Comments:

- Calculation of saturation humidity ratio W_s from $W_s = \frac{M_{H2O}}{M_a} \frac{p_{H2O,s}}{\left(p - p_{H2O,s}\right)}$

Result for Wrong Input Values:

Ws_pt_HAP_SI = -1000

References:

$p_{H2O,s}$	Herrmann et al. [1], [2]

Mass Fraction of Dry Air ξ_{Air} = f(W)

Function Name:

XiAir_W_HAP_SI

Fortran Program:

REAL*8 FUNCTION XIAIR_W_HUAIRPROP(W), REAL*8 W

Input Values:

W - Humidity ratio W in $\mathrm{kg_w/kg_a}$

Result:

XiAir_W_HAP_SI - Mass fraction of (dry) air in humid air in $\mathrm{kg_a/kg}$

Range of Validity:

Humidity ratio W: $0 \le W \le 10\,\mathrm{kg_w/kg_a}$

Comments:

- Mass fraction of (dry) air $\xi_{\mathrm{Air}} = 1 - \xi_{\mathrm{H2O}} = 1 - \dfrac{W}{1+W}$

Result for Wrong Input Values:

XiAir_W_HAP_SI = -1000

References:

$\xi_{\mathrm{Air}}(W)$ Herrmann et al. [1], [2]

Mass Fraction of Water Vapor ξ_{H2O} = f(W)

Function Name:

XiH2O_W_HAP_SI

Fortran Program:

REAL*8 FUNCTION XIH2O_W_HUAIRPROP(W), REAL*8 W

Input Values:

W - Humidity ratio W in kg_w/kg_a

Result:

XiH2O_W_HAP_SI - Mass fraction of water vapor in humid air in kg_w/kg

Range of Validity:

Humidity ratio W: $0 \le W \le 10\, kg_w/kg_a$

Comments:

- Mass fraction of water vapor $\xi_{H2O} = \dfrac{W}{1+W}$

Result for Wrong Input Values:

XiH2O_W_HAP_SI = -1000

References:

$\xi_{H2O}(W)$ Herrmann et al. [1], [2]

Compression Factor Z = f(p,t,W)

Function Name:

Z_ptW_HAP_SI

Fortran Program:

REAL*8 FUNCTION Z_PTW_HUAIRPROP(P,T,W), REAL*8 P,T,W

Input Values:

p - Total pressure p in kPa
t - Temperature t in °C
W - Humidity ratio W in $\mathrm{kg_w/kg_a}$

Result:

Z_ptW_HAP_SI - Compression factor (decimal ratio)

Range of Validity:

Total pressure p:	from 0.01 kPa to 10 000 kPa
Temperature t:	from -143.15°C to 350°C
Humidity ratio W:	$0 \le W \le W_\mathrm{s}$

Comments:

- Compression factor $Z = 1 + \frac{B_\mathrm{m}}{\bar{v}} + \frac{C_\mathrm{m}}{\bar{v}^2}$

  with $\bar{v} = \frac{M}{\rho} = \frac{M\,v}{1+W}$

  and M is the molar mass of humid air

- Calculation for supersaturated humid air ($W > W_\mathrm{s}$) is not possible

Result for Wrong Input Values:

Z_ptW_HAP_SI = -1000

References:

$B_\mathrm{m}(t,W), C_\mathrm{m}(t,W)$	Herrmann et al. [1], [2]
$\rho(p,t,W), v(p,t,W)$	Herrmann et al. [1], [2]

3.2 Functions for Steam and Water for Temperatures *t* ≥ 0°C

Specific Enthalpy of Liquid Water $h_{\text{liq}} = \mathrm{f}(p,t)$

Function Name:

hliq_pt_97_SI

Fortran Program:

```
REAL*8 FUNCTION   HLIQ_PT_97(P,T), REAL*8 P,T
```

Input Values:

p	-	Pressure p in kPa
t	-	Temperature t in °C

Result:

hliq_pt_97_SI - Specific enthalpy of liquid water in kJ/kg

Range of Validity:

Pressure p:	from $p_{\text{s}}(0°\text{C}) = 0.6112$ kPa to 10 000 kPa
Temperature t:	from 0°C to 350°C

Comments:

- Specific enthalpy of liquid water $h_{\text{liq}} = h^{97}(p,t)$ (Region 1)

Result for Wrong Input Values:

hliq_pt_97_SI = -1000

References:

$h^{97}(p,t)$	IAPWS-IF97 [7], [8]

Specific Enthalpy of Saturated Liquid Water $h_{\mathrm{liq,s}} = \mathrm{f}(t)$

Function Name:

hliqs_t_97_SI

Fortran Program:

REAL*8 FUNCTION HLIQS_T_97(T), REAL*8 T

Input Values:

t - Temperature *t* in °C

Result:

hliqs_t_97_SI - Specific enthalpy of saturated liquid water in kJ/kg

Range of Validity:

Temperature *t*: from 0°C to 350°C

Comments:

- Specific enthalpy of liquid water $h_{\mathrm{liq,s}} = h^{97}(p_{\mathrm{s}}, t)$ (Region 1)
  with $p_{\mathrm{s}} = p_{\mathrm{s}}^{97}(t)$

Result for Wrong Input Values:

hliqs_t_97_SI = -1000

References:

$h^{97}(p,t)$, $p_{\mathrm{s}}^{97}(t)$ IAPWS-IF97 [7], [8]

Specific Enthalpy of Saturated Water Vapor $h_{\text{vap,s}} = \mathrm{f}(t)$

Function Name:

hvaps_t_97_SI

Fortran Program:

REAL*8 FUNCTION HVAPS_T_97(T), REAL*8 T

Input Values:

t - Temperature *t* in °C

Result:

hvaps_t_97_SI - Specific enthalpy of saturated water vapor in kJ/kg

Range of Validity:

Temperature *t*: from 0°C to 350°C

Comments:

- Specific enthalpy of saturated water vapor $h_{\text{vap,s}} = h^{97}(p_\text{s}, t)$ (Region 2)
  with $p_\text{s} = p_\text{s}^{97}(t)$

Result for Wrong Input Values:

hvaps_t_97_SI = -1000

References:

$h^{97}(p,t)$, $p_\text{s}^{97}(t)$ IAPWS-IF97 [7], [8]

Saturation Pressure of Water p_s = f(t)

Function Name:

ps_t_97_SI

Fortran Program:

REAL*8 FUNCTION PS_T_97(T), REAL*8 T

Input Values:

t - Temperature *t* in °C

Result:

ps_t_97_SI - Saturation pressure of water in kPa

Range of Validity:

Temperature *t*: from 0°C to 350°C

Comments:

- Saturation pressure of water $p_s = p_s^{97}(t)$ (Region 4)

Result for Wrong Input Values:

ps_t_97_SI -1000

References:

$p_s^{97}(t)$ IAPWS-IF97 [7], [8]

Specific Entropy of Liquid Water $s_{\mathrm{liq}} = \mathrm{f}(p, t)$

Function Name:

sliq_pt_97_SI

Fortran Program:

REAL*8 FUNCTION   SLIQ_PT_97(P,T), REAL*8 P,T

Input Values:

p	-	Pressure p in kPa
t	-	Temperature t in °C

Result:

sliq_pt_97_SI - Specific entropy of liquid water in kJ/(kg K)

Range of Validity:

Pressure p:	from $p_{\mathrm{s}}(0°\mathrm{C}) = 0.6112$ kPa to 10 000 kPa
Temperature t:	from 0°C to 350°C

Comments:

- Specific entropy of liquid water $s_{\mathrm{liq}} = s^{97}(p,t)$ (Region 1)

Result for Wrong Input Values:

sliq_pt_97_SI = -1000

References:

$s^{97}(p,t)$	IAPWS-IF97 [7], [8]

Specific Entropy of Saturated Liquid Water $s_{\mathrm{liq,s}} = \mathrm{f}(t)$

Function Name:

sliqs_t_97_SI

Fortran Program:

REAL*8 FUNCTION SLIQS_T_97(T), REAL*8 T

Input Values:

t - Temperature *t* in °C

Result:

sliqs_t_97_SI - Specific entropy of saturated liquid water in kJ/(kg K)

Range of Validity:

Temperature *t*: from 0°C to 350°C

Comments:

- Specific entropy of liquid water $s_{\mathrm{liq,s}} = s^{97}(p_{\mathrm{s}}, t)$ (Region 1)
  with $p_{\mathrm{s}} = p_{\mathrm{s}}^{97}(t)$

Result for Wrong Input Values:

sliqs_t_97_SI = -1000

References:

$s^{97}(p,t)$, $p_{\mathrm{s}}^{97}(t)$ IAPWS-IF97 [7], [8]

Specific Entropy of Saturated Water Vapor $s_{\mathrm{vap,s}} = \mathrm{f}(t)$

Function Name:

svaps_t_97_SI

Fortran Program:

REAL*8 FUNCTION SVAPS_T_97(T), REAL*8 T

Input Values:

t - Temperature *t* in °C

Result:

svaps_t_97_SI - Specific entropy of saturated water vapor in kJ/(kg K)

Range of Validity:

Temperature *t*: from 0°C to 350°C

Comments:

- Specific entropy of saturated water vapor $s_{\mathrm{vap,s}} = s^{97}(p_{\mathrm{s}}, t)$ (Region 2)
  with $p_{\mathrm{s}} = p_{\mathrm{s}}^{97}(t)$

Result for Wrong Input Values:

svaps_t_97_SI = -1000

References:

$s^{97}(p,t)$, $p_{\mathrm{s}}^{97}(t)$ IAPWS-IF97 [7], [8]

Saturation Temperature of Water $t_s = f(p)$

Function Name:

ts_p_97_SI

Fortran Program:

```
REAL*8 FUNCTION   TS_P_97(P), REAL*8 P
```

Input Values:

p - Pressure p in kPa

Result:

ts_p_97_SI - Saturation temperature of water in °C

Range of Validity:

Pressure p: from 0.6112 kPa to 10 000 kPa

Comments:

- Saturation temperature of water $t_s = t_s^{97}(p)$ (Region 4)

Result for Wrong Input Values:

ts_p_97_SI = -1000

References:

$t_s^{97}(p)$ IAPWS-IF97 [7], [8]

Specific Volume of Liquid Water v_{liq} = f(p, t)

Function Name:

vliq_pt_97_SI

Fortran Program:

REAL*8 FUNCTION VLIQ_PT_97(P,T), REAL*8 P,T

Input Values:

p - Pressure *p* in kPa
t - Temperature *t* in °C

Result:

vliq_pt_97_SI - Specific volume of liquid water in m^3/kg

Range of Validity:

Pressure *p*: from $p_s(0°C) = 0.6112$ kPa to 10 000 kPa

Temperature *t*: from 0°C to 350°C

Comments:

- Specific volume of liquid water $v_{liq} = v^{97}(p,t)$ (Region 1)

Result for Wrong Input Values:

vliq_pt_97_SI = -1000

References:

$v^{97}(p,t)$ IAPWS-IF97 [7], [8]

Specific Volume of Saturated Liquid Water $v_{\mathrm{liq,s}}$ = f(t)

Function Name:

vliqs_t_97_SI

Fortran Program:

REAL*8 FUNCTION VLIQS_T_97(T), REAL*8 T

Input Values:

t - Temperature t in °C

Result:

vliqs_t_97_SI - Specific volume of saturated liquid water in m^3/kg

Range of Validity:

Temperature t: from 0°C to 350°C

Comments:

- Specific volume of liquid water $v_{\mathrm{liq,s}} = v^{97}(p_{\mathrm{s}}, t)$ (Region 1)

  with $p_{\mathrm{s}} = p_{\mathrm{s}}^{97}(t)$

Result for Wrong Input Values:

vliqs_t_97_SI = -1000

References:

$v^{97}(p,t)$, $p_{\mathrm{s}}^{97}(t)$ IAPWS-IF97 [7], [8]

Specific Volume of Saturated Water Vapor $v_{\mathbf{vap,s}} = \mathbf{f}(t)$

Function Name:

vvaps_t_97_SI

Fortran Program:

REAL*8 FUNCTION   VVAPS_T_97(T), REAL*8 T

Input Values:

t - Temperature *t* in °C

Result:

vvaps_t_97_SI - Specific volume of saturated water vapor in m^3/kg

Range of Validity:

Temperature *t*:	from 0°C to 350°C

Comments:

- Specific volume of saturated water vapor $v_{\text{vap,s}} = v^{97}(p_{\text{s}}, t)$ (Region 2)
  with $p_{\text{s}} = p_{\text{s}}^{97}(t)$

Result for Wrong Input Values:

vvaps_t_97_SI = -1000

References:

$v^{97}(p,t)$, $p_{\text{s}}^{97}(t)$ IAPWS-IF97 [7], [8]

3.3 Functions for Steam and Ice for Temperatures *t* ≤ 0°C

Specific Enthalpy of Saturated Ice $h_{ice,sub} = f(t)$

Function Name:

hicesub_t_06_SI

Fortran Program:

REAL*8 FUNCTION   HICESUB_T_06(T), REAL*8 T

Input Values:

t   -   Temperature *t* in °C

Result:

hicesub_t_06_SI - Specific enthalpy of saturated ice in kJ/kg

Range of Validity:

Temperature *t*:   from -143.15°C to 0°C

Comments:

- Specific enthalpy of saturated ice $h_{ice,sub} = h^{06}(p_{sub}, t)$

  with $p_{sub} = p_{sub}^{08}(t)$

Result for Wrong Input Values:

hicesub_t_06_SI = -1000

References:

$h^{06}(p,t)$	IAPWS-06 [10]
$p_{sub}^{08}(t)$	IAPWS-08 [11]

Specific Enthalpy of Saturated Water Vapor $h_{\mathrm{vap,sub}}$ = f(t)

Function Name:

hvapsub_t_95_SI

Fortran Program:

```
REAL*8 FUNCTION   HVAPSUB_T_95(T), REAL*8 T
```

Input Values:

t - Temperature t in °C

Result:

hvapsub_t_95_SI - Specific enthalpy of saturated water vapor in kJ/kg

Range of Validity:

Temperature t: from -143.15°C to 0°C

Comments:

- Specific enthalpy of saturated water vapor $h_{\mathrm{vap,sub}} = h^{95}(p_{\mathrm{sub}}, t)$

  with $p_{\mathrm{sub}} = p^{08}_{\mathrm{sub}}(t)$

Result for Wrong Input Values:

hvapsub_t_95_SI = -1000

References:

$h^{95}(p,t)$	IAPWS-95 [5], [6]
$p^{08}_{\mathrm{sub}}(t)$	IAPWS-08 [11]

Melting Pressure $p_{\mathrm{mel}} = \mathrm{f}(t)$

Function Name:

pmel_t_08_SI

Fortran Program:

REAL*8 FUNCTION PMEL_T_08 (T), REAL*8 T

Input Values:

t - Temperature *t* in °C

Result:

pmel_t_08_SI - Melting pressure of ice in kPa

Range of Validity:

Temperature *t*: from -21.985°C to 0°C

Result for Wrong Input Values:

pmel_t_08_SI = -1000

References:

$p_{\mathrm{mel}}^{08}(t)$ IAPWS-08 [11]

Sublimation Pressure p_{sub} = f(t)

Function Name:

psub_t_08_SI

Fortran Program:

```
REAL*8 FUNCTION   PSUB_T_08 (T), REAL*8 T
```

Input Values:

t - Temperature *t* in °C

Result:

psub_t_08_SI - Sublimation pressure of ice in kPa

Range of Validity:

Temperature *t*: from -143.15°C to 0°C

Result for Wrong Input Values:

psub_t_08_SI = -1000

References:

$p_{sub}^{08}(t)$ IAPWS-08 [11]

Specific Entropy of Saturated Ice $s_{\mathrm{ice,sub}} = \mathrm{f}(t)$

Function Name:

sicesub_t_06_SI

Fortran Program:

REAL*8 FUNCTION SICESUB_T_06(T), REAL*8 T

Input Values:

t - Temperature *t* in °C

Result:

sicesub_t_06_SI - Specific entropy of saturated ice in kJ/(kg K)

Range of Validity:

Temperature *t*: from -143.15°C to 0°C

Comments:

- Specific entropy of saturated ice $s_{\mathrm{ice,sub}} = s^{06}(p_{\mathrm{sub}}, t)$
  with $p_{\mathrm{sub}} = p_{\mathrm{sub}}^{08}(t)$

Result for Wrong Input Values:

sicesub_t_06_SI = -1000

References:

$s^{06}(p,t)$	IAPWS-06 [10]
$p_{\mathrm{sub}}^{08}(t)$	IAPWS-08 [11]

Specific Entropy of Saturated Water Vapor $s_{\mathrm{vap,sub}} = \mathrm{f}(t)$

Function Name:

svapsub_t_95_SI

Fortran Program:

```
REAL*8 FUNCTION   SVAPSUB_T_95(T), REAL*8 T
```

Input Values:

t - Temperature t in °C

Result:

svapsub_t_95_SI - Specific entropy of saturated water vapor in kJ/(kg K)

Range of Validity:

Temperature t: from -143.15°C to 0°C

Comments:

- Specific entropy of saturated water vapor $s_{\mathrm{vap,sub}} = s^{95}(p_{\mathrm{sub}}, t)$
  with $p_{\mathrm{sub}} = p_{\mathrm{sub}}^{08}(t)$

Result for Wrong Input Values:

svapsub_t_95_SI = -1000

References:

$s^{95}(p,t)$	IAPWS-95 [7], [8]
$p_{\mathrm{sub}}^{08}(t)$	IAPWS-08 [11]

Melting Temperature $t_{\mathrm{mel}} = \mathrm{f}(p)$

Function Name:

tmel_p_08_SI

Fortran Program:

REAL*8 FUNCTION TMEL_P_08(P), REAL*8 P

Input Values:

p - Pressure *p* in kPa

Result:

tmel_p_08_SI - Melting temperature of ice in °C

Range of Validity:

Pressure *p*:	from $p_{\mathrm{s}}(0°\mathrm{C}) = 0.6112$ kPa to 10 000 kPa

Result for Wrong Input Values:

tmel_p_08_SI = -1000

References:

$t_{\mathrm{mel}}^{08}(p)$	IAPWS-08 [11]

Sublimation Temperature t_{sub} = f(p)

Function Name:

tsub_p_08_SI

Fortran Program:

REAL*8 FUNCTION   TSUB_P_08(P), REAL*8 P

Input Values:

p - Pressure p in kPa

Result:

tsub_p_08_SI - Sublimation temperature of ice in °C

Range of Validity:

Pressure p: from $p_{\mathrm{subl}}(-143.15°\mathrm{C}) = 1.2002 \times 10^{-11}$ kPa to $p_{\mathrm{subl}}(0°\mathrm{C}) = 0.6112$ kPa

Result for Wrong Input Values:

tsub_p_08_SI = -1000

References:

$t_{\mathrm{sub}}^{08}(p)$	IAPWS-08 [11]

Specific Volume of Saturated Ice $v_{\text{ice,sub}} = f(t)$

Function Name:

vicesub_t_06_SI

Fortran Program:

`REAL*8 FUNCTION VICESUB_T_06(T), REAL*8 T`

Input Values:

t - Temperature *t* in °C

Result:

vicesub_t_06_SI - Specific volume of saturated ice in m^3/kg

Range of Validity:

Temperature *t*: from -143.15°C to 0°C

Comments:

- Specific volume of saturated ice $v_{\text{ice,sub}} = v^{06}(p_{\text{sub}}, t)$
  with $p_{\text{sub}} = p_{\text{sub}}^{08}(t)$

Result for Wrong Input Values:

vicesub_t_06_SI = -1000

References:

$v^{06}(p,t)$	IAPWS-06 [10]
$p_{\text{sub}}^{08}(t)$	IAPWS-08 [11]

Specific Volume of Saturated Water Vapor $v_{\mathrm{vap,sub}} = \mathrm{f}(t)$

Function Name:

vvapsub_t_95_SI

Fortran Program:

REAL*8 FUNCTION VVAPSUB_T_95(T), REAL*8 T

Input Values:

t - Temperature *t* in °C

Result:

vvapsub_t_95_SI - Specific volume of saturated water vapor in m^3/kg

Range of Validity:

Temperature *t*: from -143.15°C to 0°C

Comments:

- Specific volume of saturated water vapor $v_{\mathrm{vap,sub}} = v^{95}(p_{\mathrm{sub}}, t)$

  with $p_{\mathrm{sub}} = p_{\mathrm{sub}}^{08}(t)$

Result for Wrong Input Values:

vvapsub_t_95_SI = -1000

References:

$v^{95}(p,t)$	IAPWS-95 [7], [8]
$p_{\mathrm{sub}}^{08}(t)$	IAPWS-08 [11]

4. Property Libraries for Calculating Heat Cycles, Boilers, Turbines and Refrigerators

Water and Steam

Library LibIF97

- Industrial Formulation IAPWS-IF97 (Revision 2007)
- Supplementary Standards IAPWS-IF97-S01, -S03rev, -S04, and -S05
- IAPWS Revised Advisory Note No. 3 on Thermodynamic Derivatives (2008)

Library LibIF97_META

- Industrial Formulation IAPWS-IF97 (Revision 2007) for metastable steam

Humid Combustion Gas Mixtures

Library LibHuGas

Model: Ideal mixture of the real fluids:

CO_2 - Span, Wagner H_2O - IAPWS-95
O_2 - Schmidt, Wagner N_2 - Span et al.
Ar - Tegeler et al.

and of the ideal gases:

SO_2, CO, Ne
(Scientific Formulation of Bücker et al.)

Consideration of:

- Dissociation from VDI 4670
- Poynting effect

Humid Air

Library LibHuAir

Model: Ideal mixture of the real fluids:

- Dry air from Lemmon et al.
- Steam, water and ice from IAPWS-IF97 and IAPWS-06

Consideration of:

- Condensation and freezing of steam
- Dissociation from VDI 4670
- Poynting effect from ASHRAE RP-1485

Extremely Fast Property Calculations

Spline-Based Table Look-up Method (SBTL)

Library LibSBTL_IF97
Library LibSBTL_95
Library LibSBTL_HuAir

For steam, water, humid air, carbon dioxide and other fluids and mixtures according IAPWS Guideline 2015 for Computational Fluid Dynamics (CFD), real-time and non-stationary simulations

Carbon Dioxide Including Dry Ice

Library LibCO2

Formulation of Span and Wagner (1996)

Seawater

Library LibSeaWa

IAPWS Industrial Formulation 2013

Ice

Library LibICE

Ice from IAPWS-06, Melting and sublimation pressures from IAPWS-08, Water from IAPWS-IF97, Steam from IAPWS-95 and -IF97

Ideal Gas Mixtures

Library LibIdGasMix

Model: Ideal mixture of the ideal gases:

Ar
Ne
N_2
O_2
CO
CO_2
Air
NO
H_2O
SO_2
H_2
H_2S
OH
He
F_2
NH_3
Methane
Ethane
Ethylene
Propylene
Propane
Iso-Butane
n-Butane
Benzene
Methanol

Consideration of:

- Dissociation from the VDI Guideline 4670

Library LibIDGAS

Model: Ideal gas mixture from VDI Guideline 4670

Consideration of:

- Dissociation from the VDI Guideline 4670

Humid Air

Library ASHRAE LibHuAirProp

Model: Virial equation from ASHRAE Report RP-1485 for real mixture of the real fluids:
- Dry air
- Steam

Consideration of:

- Enhancement of the partial saturation pressure of water vapor at elevated total pressures

www.ashrae.org/bookstore

Dry Air Including Liquid Air

Library LibRealAir

Formulation of Lemmon et al. (2000)

Refrigerants

Ammonia

Library LibNH3

Formulation of Tillner-Roth et al. (1993)

R134a

Library LibR134a

Formulation of Tillner-Roth and Baehr (1994)

Iso-Butane

Library LibButane_Iso

Formulation of Bücker and Wagner (2006)

n-Butane

Library LibButane_n

Formulation of Bücker and Wagner (2006)

Mixtures for Absorption Processes

Ammonia/Water Mixtures

Library LibAmWa

IAPWS Guideline 2001 of Tillner-Roth and Friend (1998)

Helmholtz energy equation for the mixing term

(also useable for calculating the Kalina Cycle)

Water/Lithium Bromide Mixtures

Library LibWaLi

Formulation of Kim and Infante Ferreira (2004)

Gibbs energy equation for the mixing term

Liquid Coolants

Liquid Secondary Refrigerants

Library LibSecRef

Liquid solutions of water with

$C_2H_6O_2$	Ethylene glycol
$C_3H_8O_2$	Propylene glycol
C_2H_5OH	Ethanol
CH_3OH	Methanol
$C_3H_8O_3$	Glycerol
K_2CO_3	Potassium carbonate
$CaCl_2$	Calcium chloride
$MgCl_2$	Magnesium chloride
NaCl	Sodium chloride
$C_2H_3KO_2$	Potassium acetate
$CHKO_2$	Potassium formate
LiCl	Lithium chloride
NH_3	Ammonia

Formulation of the International Institute of Refrigeration (IIR 2010)

Ethanol

Library LibC2H5OH

Formulation of
Schroeder et al. (2014)

Methanol

Library LibCH3OH

Formulation of
de Reuck and Craven (1993)

Propane

Library LibPropane

Formulation of
Lemmon et al. (2009)

Siloxanes as ORC Working Fluids

Octamethylcyclotetrasiloxane	$C_8H_{24}O_4Si_4$	**Library LibD4**
Decamethylcyclopentasiloxane	$C_{10}H_{30}O_5Si_5$	**Library LibD5**
Tetradecamethylhexasiloxane	$C_{14}H_{42}O_5Si_6$	**Library LibMD4M**
Hexamethyldisiloxane	$C_6H_{18}OSi_2$	**Library LibMM**

Formulation of Colonna et al. (2006)

Dodecamethylcyclohexasiloxane	$C_{12}H_{36}O_6Si_6$	**Library LibD6**
Decamethyltetrasiloxane	$C_{10}H_{30}O_3Si_4$	**Library LibMD2M**
Dodecamethylpentasiloxane	$C_{12}H_{36}O_4Si_5$	**Library LibMD3M**
Octamethyltrisiloxane	$C_8H_{24}O_2Si_3$	**Library LibMDM**

Formulation of Colonna et al. (2008)

Nitrogen and Oxygen

**Libraries
LibN2 and LibO2**

Formulations of Span et al. (2000)
and Schmidt and Wagner (1985)

Hydrogen

Library LibH2

Formulation of
Leachman et al. (2009)

Helium

Library LibHe

Formulation of
Arp et al. (1998)

Hydrocarbons

Decane	$C_{10}H_{22}$	**Library LibC10H22**
Isopentane	C_5H_{12}	**Library LibC5H12_Iso**
Neopentane	C_5H_{12}	**Library LibC5H12_Neo**
Isohexane	C_6H_{14}	**Library LibC6H14**
Toluene	C_7H_8	**Library LibC7H8**

Formulation of Lemmon and Span (2006)

Further Fluids

Carbon monoxide	CO	**Library LibCO**
Carbonyl sulfide	COS	**Library LibCOS**
Hydrogen sulfide	H_2S	**Library LibH2S**
Nitrous oxide	N_2O	**Library LibN2O**
Sulfur dioxide	SO_2	**Library LibSO2**
Acetone	C_3H_6O	**Library LibC3H6O**

Formulation of Lemmon and Span (2006)

KCE
ThermoFluidProperties

For more information please contact:

KCE-ThermoFluidProperties UG
Prof. Dr. Hans-Joachim Kretzschmar
Haager Weg 6
92224 Amberg, Germany

Internet: www.thermofluidprop.com
Email: info@thermofluidprop.com
Phone: +49-9621-1762047
Mobile: +49-172-7914607
Fax: +49-3222-1095810

The following thermodynamic and transport properties can be calculated[a]:

Thermodynamic Properties

- Vapor pressure p_s
- Saturation temperature T_s
- Density ρ
- Specific volume v
- Enthalpy h
- Internal energy u
- Entropy s
- Exergy e
- Isobaric heat capacity c_p
- Isochoric heat capacity c_v
- Isentropic exponent κ
- Speed of sound w
- Surface tension σ

Transport Properties

- Dynamic viscosity η
- Kinematic viscosity ν
- Thermal conductivity λ
- Prandtl number Pr
- Thermal diffusivity a

Backward Functions

- T, v, s (p,h)
- T, v, h (p,s)
- p, T, v (h,s)
- p, T (v,h)
- p, T (v,u)

Thermodynamic Derivatives

- Partial derivatives used in process modeling can be calculated.

---

[a] Not all of these property functions are available in all property libraries.

www.thermofluidprop.com

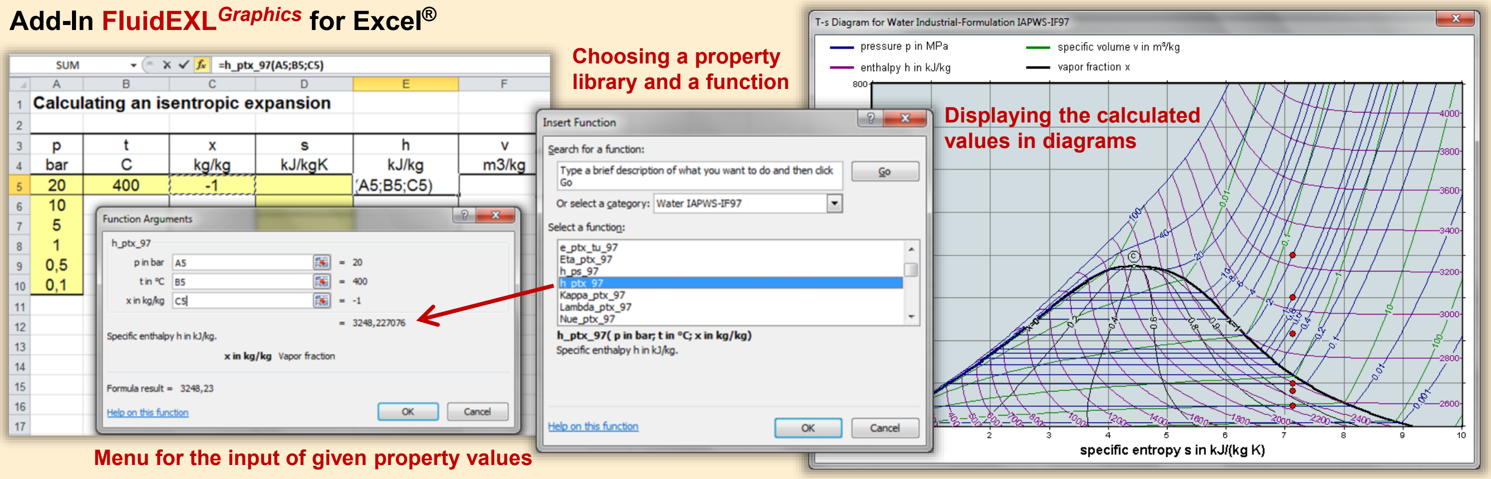
KCE
ThermoFluidProperties

KCE-ThermoFluidProperties
www.thermofluidprop.com

Hochschule Zittau/Görlitz
UNIVERSITY OF APPLIED SCIENCES

Property Software for Calculating Heat Cycles, Boilers, Turbines and Refrigerators

Add-In **FluidEXL*Graphics*** for Excel®



SUM =h_ptx_97(A5;B5;C5)

Calculating an isentropic expansion

p	t	x	s	h	v
bar	C	kg/kg	kJ/kgK	kJ/kg	m3/kg
20	400	-1		(A5;B5;C5)	
10					
5					
1					
0,5					
0,1					

Function Arguments
h_ptx_97
p in bar A5 = 20
t in °C B5 = 400
x in kg/kg C5 = -1
= 3248,227076
Specific enthalpy h in kJ/kg.
x in kg/kg Vapor fraction
Formula result = 3248,23

Insert Function
Search for a function: Type a brief description of what you want to do and then click Go
Or select a category: Water IAPWS-IF97
Select a function: e_ptx_tu_97, Eta_ptx_97, h_ps_97, h_ptx_97, Kappa_ptx_97, Lambda_ptx_97, Nue_ptx_97
h_ptx_97(p in bar; t in °C; x in kg/kg)
Specific enthalpy h in kJ/kg.

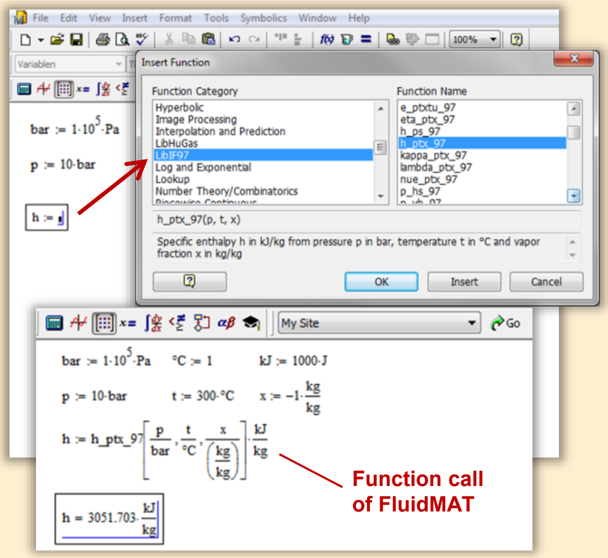
Choosing a property library and a function

Displaying the calculated values in diagrams

Menu for the input of given property values

Add-On **FluidMAT** for Mathcad®
Add-On **FluidPRIME** for Mathcad Prime®

The property libraries can be used in Mathcad® and Mathcad Prime®.



Insert Function
Function Category: Hyperbolic, Image Processing, Interpolation and Prediction, LibHuGas, LibIF97, Log and Exponential, Lookup, Number Theory/Combinatorics
Function Name: e_ptxtu_97, eta_ptx_97, h_ps_97, h_ptx_97, kappa_ptx_97, lambda_ptx_97, nue_ptx_97, p_hs_97
h_ptx_97(p, t, x)
Specific enthalpy h in kJ/kg from pressure p in bar, temperature t in °C and vapor fraction x in kg/kg

$bar := 1 \cdot 10^5 \cdot Pa$ $\quad °C := 1$ $\quad kJ := 1000 \cdot J$

$p := 10 \cdot bar$ $\quad t := 300 \cdot °C$ $\quad x := -1 \cdot \frac{kg}{kg}$

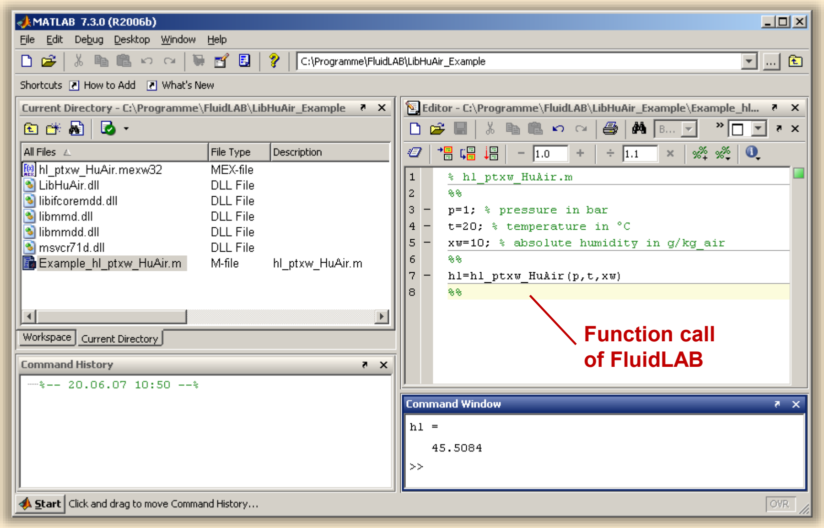
$h := h\_ptx\_97\left[\frac{p}{bar}, \frac{t}{°C}, \frac{x}{\left(\frac{kg}{kg}\right)}\right] \cdot \frac{kJ}{kg}$

$h = 3051.703 \frac{kJ}{kg}$

Function call of FluidMAT

Add-On **FluidLAB** for MATLAB® and SIMULINK®

Using the Add-In FluidLAB the property functions can be called in MATLAB® and SIMULINK®.



MATLAB 7.3.0 (R2006b)
Current Directory - C:\Programme\FluidLAB\LibHuAir_Example

All Files	File Type	Description
hl_ptxw_HuAir.mexw32	MEX-file	
LibHuAir.dll	DLL File	
libifcoremdd.dll	DLL File	
libmmd.dll	DLL File	
libmmdd.dll	DLL File	
msvcr71d.dll	DLL File	
Example_hl_ptxw_HuAir.m	M-file	hl_ptxw_HuAir.m

Command History: --%-- 20.06.07 10:50 --%

```
% hl_ptxw_HuAir.m
%%
p=1; % pressure in bar
t=20; % temperature in °C
xw=10; % absolute humidity in g/kg_air
%%
hl=hl_ptxw_HuAir(p,t,xw)
%%
```

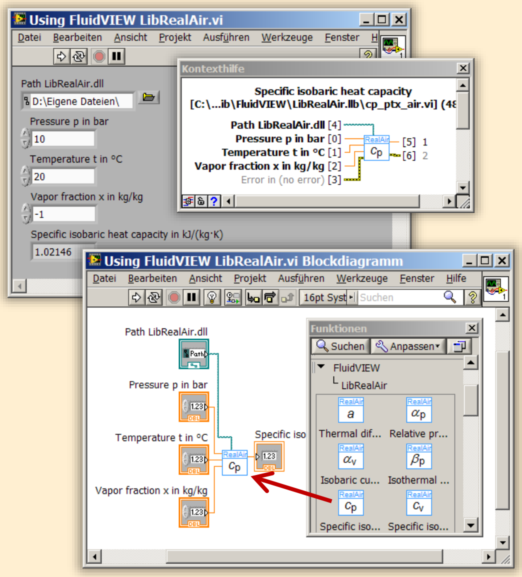
Command Window

```
hl =

   45.5084

>>
```

Function call of FluidLAB

Add-On **FluidVIEW** for LabVIEW™

The property functions can be calculated in LabVIEW™.



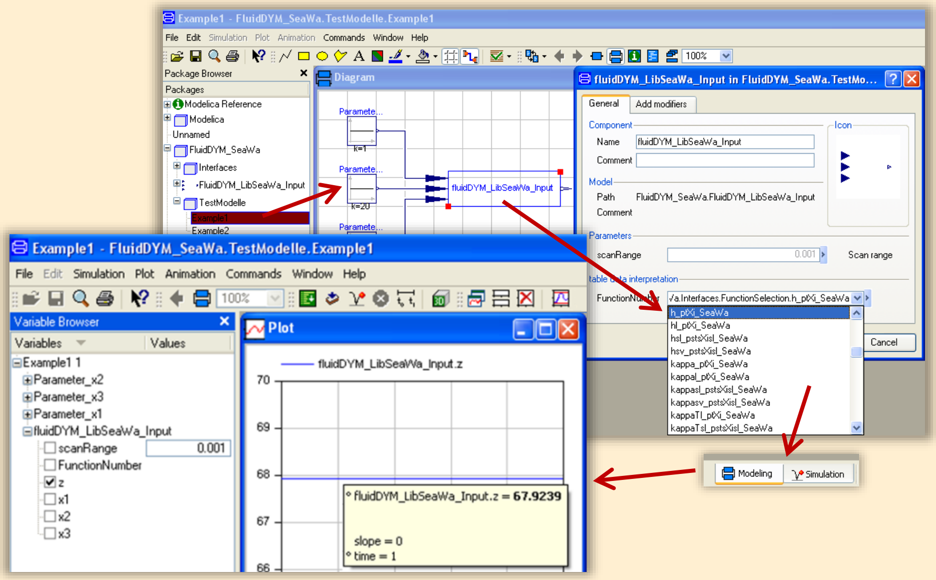
Using FluidVIEW LibRealAir.vi
Path LibRealAir.dll: D:\Eigene Dateien\
Pressure p in bar: 10
Temperature t in °C: 20
Vapor fraction x in kg/kg: -1
Specific isobaric heat capacity in kJ/(kg·K): 1.02146

Kontexthilfe
Specific isobaric heat capacity
[C:\...ib\FluidVIEW\LibRealAir.llb\cp_ptx_air.vi] (4
Path LibRealAir.dll [4]
Pressure p in bar [0]
Temperature t in °C [1]
Vapor fraction x in kg/kg [2]
Error in (no error) [3]

Using FluidVIEW LibRealAir.vi Blockdiagramm

Add-On **FluidDYM** for DYMOLA® (Modelica) and SimulationX®

The property functions can be called in DYMOLA® and SimulationX®.



Example1 - FluidDYM_SeaWa.TestModelle.Example1

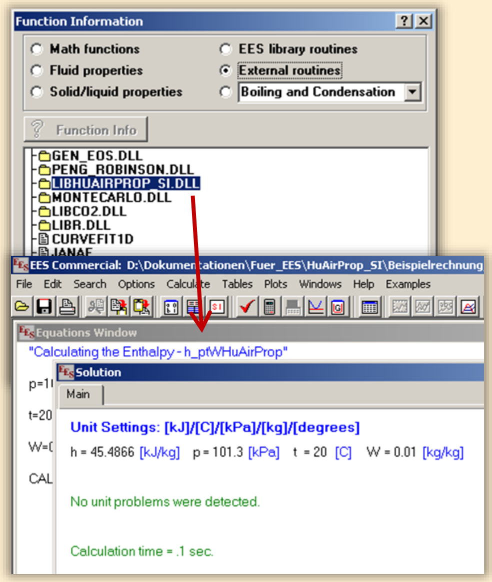
fluidDYM_LibSeaWa_Input in FluidDYM_SeaWa.TestMo...
Component
Name: fluidDYM_LibSeaWa_Input
Model
Path: FluidDYM_SeaWa.FluidDYM_LibSeaWa_Input
Parameters
scanRange: 0.001 Scan range
FunctionNumber: .a.Interfaces.FunctionSelection.h_pXi_SeaWa
h_pXi_SeaWa, hl_pXi_SeaWa, hsl_pstsXisl_SeaWa, hsv_pstsXisl_SeaWa, kappa_pXi_SeaWa, kappal_pXi_SeaWa, kappasl_pstsXisl_SeaWa, kappasv_pstsXisl_SeaWa, kappaTl_pXi_SeaWa, kappaTsl_pstsXisl_SeaWa

Variable Browser

Variables	Values
Example1 1	
Parameter_x2	
Parameter_x3	
Parameter_x1	
fluidDYM_LibSeaWa_Input	
☐ scanRange	0.001
☐ FunctionNumber	
☑ z	
☐ x1	
☐ x2	
☐ x3	

Plot: fluidDYM_LibSeaWa_Input.z
fluidDYM_LibSeaWa_Input.z = 67.9239
slope = 0
time = 1

Add-On FluidEES for Engineering Equation Solver®



○ Math functions ○ EES library routines
○ Fluid properties ● External routines
○ Solid/liquid properties ○ Boiling and Condensation

GEN_EOS.DLL
PENG_ROBINSON.DLL
LIBHUAIRPROP_SI.DLL
MONTECARLO.DLL
LIBCO2.DLL
LIBR.DLL
CURVEFIT1D
JANAF

EES Commercial: D:\Dokumentationen\Fuer_EES\HuAirProp_SI\Beispielrechnung

"Calculating the Enthalpy - h_ptWHuAirProp"

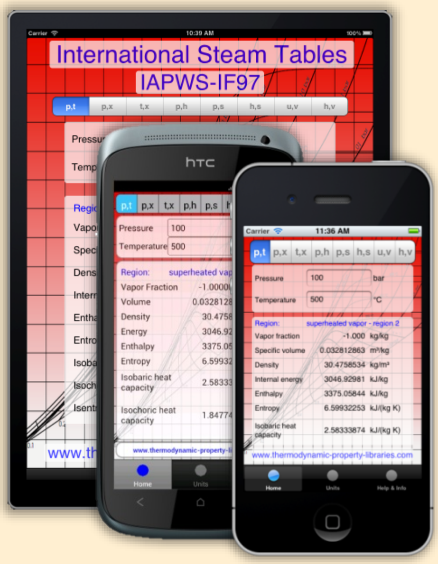
Unit Settings: [kJ]/[C]/[kPa]/[kg]/[degrees]

h = 45.4866 [kJ/kg] p = 101.3 [kPa] t = 20 [C] W = 0.01 [kg/kg]

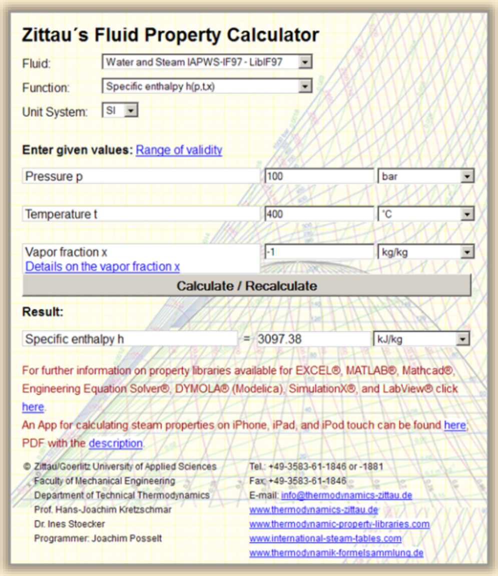
No unit problems were detected.

Calculation time = .1 sec.

App International Steam Tables for iPhone, iPad, iPod touch, Android Smartphones and Tablets



Online Property Calculator at www.thermofluidprop.com



Zittau´s Fluid Property Calculator

Fluid: Water and Steam IAPWS-IF97 - LibIF97
Function: Specific enthalpy h(p,t,x)
Unit System: SI

Enter given values: Range of validity

Pressure p 100 bar
Temperature t 400 °C
Vapor fraction x -1 kg/kg
Details on the vapor fraction x

Result:

Specific enthalpy h = 3097.38 kJ/kg

For further information on property libraries available for EXCEL®, MATLAB®, Mathcad®, Engineering Equation Solver®, DYMOLA® (Modelica), SimulationX®, and LabView® click here.

An App for calculating steam properties on iPhone, iPad, and iPod touch can be found here, PDF with the description.

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Dr. Ines Stoecker
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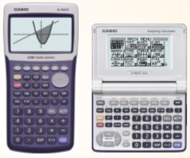
www.thermodynamics-zittau.de
www.thermodynamic-property-libraries.com
www.international-steam-tables.com
www.thermodynamik-formelsammlung.de

Property Software for Pocket Calculators

FluidCasio


fx 9750 G II

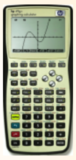

CFX 9850
fx-GG20


CFX 9860 G
Graph 85


ALGEBRA
FX 2.0

FluidHP


HP 48


HP 49

FluidTI


TI Nspire CX CAS
TI Nspire CAS


TI 83
TI 84
TI 89


TI Voyage 200


TI 92

For more information please contact:

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Mobile: +49-172-7914607
Fax: +49-3222-1095810

The following thermodynamic and transport properties[a] can be calculated in Excel®, MATLAB®, Mathcad®, Engineering Equation Solver® (EES), DYMOLA® (Modelica), SimulationX® and LabVIEW™:

Thermodynamic Properties

- Vapor pressure p_s
- Saturation temperature T_s
- Density ρ
- Specific volume v
- Enthalpy h
- Internal energy u
- Entropy s
- Exergy e
- Isobaric heat capacity c_p
- Isochoric heat capacity c_v
- Isentropic exponent κ
- Speed of sound w
- Surface tension σ

Transport Properties

- Dynamic viscosity η
- Kinematic viscosity ν
- Thermal conductivity λ
- Prandtl number Pr
- Thermal diffusivity a

Backward Functions

- T, v, s (p,h)
- T, v, h (p,s)
- p, T, v (h,s)
- p, T (v,h)
- p, T (v,u)

Thermodynamic Derivatives

- Partial derivatives used in process modeling can be calculated.

---

[a] Not all of these property functions are available in all property libraries.

www.thermofluidprop.com

5 References

[1] Herrmann, S.; Kretzschmar, H.-J.; Gatley, D.P.: Thermodynamic Properties of Real Moist Air, Dry Air, Steam, Water, and Ice. HVAC&R Research 5, 961-986 (2009).

[2] Herrmann, S.; Kretzschmar, H.-J.; Gatley, D.P.: Thermodynamic Properties of Real Moist Air, Dry Air, Steam, Water, and Ice. ASHRAE RP-1485, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, GA (2009).

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[16] IAPWS. G7-04, Guideline on the Henry's Constant and Vapor-Liquid Distribution Constant for Gases in H_2O and D_2O at High Temperatures. (2004), available from www.iapws.org.

[17] Gatley, D.P.; Herrmann, S.; Kretzschmar, H.-J.: A Twenty-First Century Molar Mass for Dry Air. HVAC&R Research 14, 655-662 (2008).

[18] Lemmon, E.W.; Jacobsen, R.T.: Viscosity and Thermal Conductivity Equations for Nitrogen, Oxygen, Argon, and Air. Int. J. Thermophys. 25, 21-69 (2004).

[19] IAPWS. R12-08, Release on the IAPWS Formulation 2008 for the Viscosity of Ordinary Water Substance. (2008), available from www.iapws.org.

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6 Satisfied Customers

Period from 2018 to 2022

The following companies and institutions use the property libraries:

- FluidEXL$^{\mathit{Graphics}}$ for Excel® incl. VBA
- FluidLAB for MATLAB® and Simulink
- FluidMAT for Mathcad®
- FluidPRIME for Mathcad Prime®
- FluidEES for Engineering Equation Solver® EES
- FluidDYM for Dymola® (Modelica) and SimulationX®
- FluidVIEW for LabVIEW™
- FluidPYT for Python
- FluidJAVA for Java
- DLLs for Windows Applications
- Shared Objects for Linux
- Shared Objects for macOS.

2022

ASTG, Graz, Austria	12/2022
Wandschneider + Gutjahr, Hamburg	
RWE Supply & Trading, Essen	11/2022
Stadtwerke Rosenheim	
CEA, Saclay, France	10/2022
RWE Supply & Trading, Essen	
SEEC Saudi Energy Efficiency Center, Riyadh, Saudi Arabia	
MAN, Copenhagen, Denmark	
Hermeler & Partner Consulting Engineers, Sassenberg	09/2022
Envi Con, Nürnberg	
Drill Cool Systems, Bakersfield CA, USA	
RWE Supply & Trading, Essen	
Maerz Ofenbau, Zürich, Switzerland	
Saale Energie, Schkopau	
ERGO, Dresden	
Mainova, Frankfurt/Main	
Bundeswehr, Koblenz	08/2022
RWE Supply & Trading, Essen	
Grenzebach Corporation, Newnan GE, USA	
AGRANA, Gmuend, Austria	07/2022
MIBRAG, Zeitz	
Hochschule Niederrhein, Krefeld	
ULT, Löbau	06/2022
LEAG, Cottbus	

VPC Group, Vetschau	
Wärme, Hamburg	
ILK, Dresden	
Stricker IB, Küssnacht a. Rigi, Switzerland	
LEAG, Cottbus	05/2022
RWE Supply & Trading, Essen	
IGT Tomalla, Kreuztal	
B+T Engineering, Dübendorf, Switzerland	
Stricker IB, Küssnacht a. Rigi, Switzerland	
Vogelsang & Benning, Bochum	04/2022
Frischli, Rehburg-Loccum	
BPS Consulting, Sprenge	03/2022
HS Hannover, Maschinenbau & BioVT	
M+M Turbinentechnik, Bad Salzuflen	
Uni. Strathclyde, Glasgow, UK	02/2022
Delta Energy Group, Jiaozhou City, Qingdao, China	
Wetzel IB, Guben	
Wijbenga, PC Geldermalsen, The Netherlands	
Voith Paper, Heidenheim	
HS Zittau/Görlitz, Maschinenwesen	01/2022
Thermische Abfallbehandlung, Lauta	
Webb Institute, Glen Cove NY, USA	
TU Berlin, Umweltverfahrenstechnik	
SachsenEnergie, Dresden	
Doosan, Chang-won-si, Gyeongsangnam-do, South Korea	
KW3, LH Veenendaal, The Netherlands	
Université du Luxembourg, Esch-sur-Alzette	
Enseleit IB, Mansfeld	
Caliqua/Equans, Zürich, Switzerland	
Rudnick & Enners, Alpenrod	

2021

Wenisch IB, Vetschau	12/2021
PPCHEM, Hinwil, Switzerland	
KW3, The Netherlands	
BASF Ludwigshafen	
Air-Consult, Jena	
Sjerp & Jongeneel, RB Zoetermeer, The Netherlands	11/2021
Maerz Ofenbau, Zürich, Switzerland	
RWE Supply & Trading, Essen	
Hahn IB, Dresden	10/2021
Therm, South Africa	
RWE Supply & Trading, Essen	
TH Nürnberg, Verfahrenstechnik	09/2021
RWE Supply & Trading, Essen	
Enseleit IB, Mansfeld	

SachsenEnergie, Dresden	
BSH Hausgeräte, Berlin	
Norsk Energi, Oslo, Norway	08/2021
AKM Industrieanlagen, Haltern	
Drill Cool Systems, Bakersfield CA, USA	
Siemens Energy Global, Erlangen	07/2021
Wulff & Umag, Husum	
Planungsbüro Waidhas, Chemnitz	
Burkhardt Energie Technik, Mühlhausen	
Lücke IB, Paderborn	06/2021
TU Dresden, Energieverfahrenstechnik	
Wärme, Hamburg	
AL-KO Therm, Kötz	
PCK Raffinerie, Schwedt	
Vogelsang & Benning, Bochum	05/2021
MTU, München	
VPC Group, Vetschau	
AVG, Köln	04/2021
TH Ulm, Institut für Fahrzeugtechnik	
Marty IB, Oberwil, Switzerland	
HypTec, Lebring, Austria	
Lopez IB, Getxo, Bizkaia, Spain	03/2021
GM Remediation Systems, Leoben, Austria	
Jager Kältetechnik, Osnabrück	
T&M Automation, GR Leidschendam, The Netherlands	
RWE Supply & Trading, Essen	
Stadtwerke Leipzig	
Beuth Hochschule für Technik, Berlin	
Beleth IB, Woeth	02/2021
ZTL, Thal, Austria	
ETABO Bochum	
RWE Supply & Trading, Essen	
Onyx Germany, Berlin	
TU Dresden, Kältetechnik	
GOHL-KTK, Durmersheim	
Therm Development, South Africa	
thermofin, Heinsdorfergrund	
RWE Supply & Trading, Essen	01/2021
STEAG, Essen	
ETA Energieberatung, Pfaffenhofen	
Enex Power, Kirchseeon	

2020

Drill Cool, Bakersfield CA, USA	12/2020
Manders, The Netherlands	
RWE Supply & Tranding, Essen	

NEOWAT Lodz, Poland	
University of Duisburg-Essen, Duisburg	11/2020
Stellenbosch University, South Africa	
University De France-COMTe, France	
RWE, Essen	
STEAG, Herne	
Isenmann Ingenierbüro	
University of Stuttgart, ITLR, Stuttgart	
Norsk Energi, Oslo, Norway	
TGM Kanis, Nürnberg	
Stadtwerke Neuburg	10/2020
Smurfit Kappa, Roermond, The Netherlands	
RWE, Essen	
Hochschule Zittau/Görlitz, Wirtschaftsingenieurwesen	
Stadtwerke, Neuburg	
ILK, Dresden	
ATESTEO, Alsdorf	
Hochschule Zittau/Görlitz, Maschinenwesen	
TH Nürnberg, Verfahrenstechnik	
Drill Cool, Bakersfield CA,USA	09/2020
RWE, Essen	
2Meyers Ingenieurbüro, Nürnberg	
FELUWA, Mürlenbach	
Stadtwerke Neuburg	
Caverion, Wien, Austria	
GMVA Niederrhein, Oberhausen	
INWAT Lodz, Poland	
Troche Ingenieurbüro, Hayingen	08/2020
CEA Saclay, France	
VPC, Vetschau	07/2020
FSK System-Kälte-Klima, Dortmund	
Exergie Etudes, Sarl, Switzerland	
AWG Wuppertal	
STEAG Energy Services, Zwingenberg	
Hochschule Braunschweig	06/2020
DBI, Leipzig	
GOHL-KTK, Dumersheim	
TU Dresden, Energieverfahrenstechnik	
BASF SE, ESI/EE, Ludwigshafen	
Wärme Hamburg	
Ruchti Ingenieurbüro, Uster, Switzerland	
IWB, Basel, Switzerland	
Midiplan, Bietingen-Bissingen	05/2020
Knieschke, Ingenieurbüro	
RWE, Essen	
Leser, Hamburg	

AGRANA, Gmünd, Austria	
EWT Wassertechnik, Celle	
Hochschule Darmstadt	04/2020
MTU München CCP	
HAW Hamburg	03/2020
Hanon, Novi Jicin, Czech Republic	
TU Dresden, Kältetechnik	
MAN, Copenhagen, Denmark	
EnerTech, Radebeul	02/2020
LEAG, Cottbus	
B+B Enginering Magdeburg	
Hochschule Offenburg	
WIB, Dennheritz	01/2020
Universität Duisburg-Essen, Strömungsmaschinen	
Kältetechnik Dresen-Bremen	
TH Ingolstadt	
Vattenfall AB, Jokkmokk, Sweden	
Fraunhofer UMSICHT	

2019

PEU Leipzig, Rötha	12/2019
MB-Holding, Vestenbergsgreuth	
RWE, Essen	
Georg-Büchner-Hochschule, Darmstadt	11/2019
EEB ENERKO, Aldenhoven	
Robert Benoufa Energietechnik, Wiesloch	
Kehrein & Kubanek Klimatechnik, Moers	10/2019
Hanon Systems Autopal Services, Hluk, Czech Republic	
CEA Saclay, Gif Sur Yvette cedex, France	
Saudi Energy Efficiency Center SEEC, Riyadh, Saudi Arabia	
VPC, Vetschau	09/2019
jGanser PM + Engineering, Forchheim	
Endress+Hauser Flowtec AG, Reinach, Switzerland	
Ruchti IB, Uster, Switzerland	
ZWILAG Zwischenlager Würenlingen, Switzerland	08/2019
Hochschule Zittau/Görlitz, Faculty Maschinenwesen	
Stadtwerke Neubrandenburg	
Physikalisch Technische Bundesanstalt PTB, Braunschweig	
GMVA Oberhausen	07/2019
Endress+Hauser Flowtec AG, Reinach, Switzerland	
WARNICA, Waterloo, Canada	
MIBRAG, Zeitz	06/2019
Pöyry, Zürich, Switzerland	
RWTH Aachen, Institut für Strahlantriebe und Turbomaschinen	
Midiplan, Bietigheim-Bissingen	
GKS Schweinfurt	

HS Zittau/Görlitz, Wirtschaftswissenschaften und Wirtschaftsingenieurwesen	
ILK Dresden	
HZDR Helmholtz Zentrum Dresden-Rossendorf	
TH Köln, Technische Gebäudeausrüstung	05/2019
IB Knittel, Braunschweig	
Norsk Energi, Oslo, Norway	
STEAG, Essen	
Stora Enso, Eilenburg	
IB Lücke, Paderborn	
Haarslev, Sonderso, Denmark	
MAN Augsburg	
Wieland Werke, Ulm	04/2019
Fels-Werke, Elbingerode	
Univ. Luxembourg, Luxembourg	
BTU Cottbus, Power Engineering	03/2009
Eins-Energie Sachsen, Schwarzenberg	
TU Dresden, Kälte- und Kryotechnik	
ITER, St. Paul Lez Durance Cedex, France	
Fraunhofer UMSICHT, Oberhausen	
Comparex Leipzig for Spedition Thiele HEMMERSBACH	
Rückert NaturGas, Lauf/Pegnitz	
BASF, Basel, Switzerland	02/2019
Stadtwerke Leipzig	
Maerz Ofenbau Zürich, Switzerland	
Hanon Systems Germany, Kerpen	
Thermofin, Heinsdorfergrund	01/2019
BSH Berlin	

2018

Jaguar Energy, Guatemala	12/2018
WEBASTO, Gilching	
Smurfit Kappa, Oosterhout, Netherlands	
Univ. BW München	
RAIV, Liberec for VALEO, Prague, Czech Republic	11/2018
VPC Group Vetschau	
SEITZ, Wetzikon, Switzerland	
MVV, Mannheim	10/2018
IB Troche	
KANIS Turbinen, Nürnberg	
TH Ingolstadt, Institut für neue Energiesysteme	
IB Kristl & Seibt, Graz, Austria	09/2018
INEOS, Köln	
IB Lücke, Paderborn	
Südzucker, Ochsenfurt	08/2018
K&K Turbinenservice, Bielefeld	07/2018
OTH Regensburg, Elektrotechnik	

Comparex Leipzig for LEAG, Berlin	06/2018
Münstermann, Telgte	05/2018
TH Nürnberg, Verfahrenstechnik	
Universität Madrid, Madrid, Spanien	
HS Zittau/Görlitz, Wirtschaftsingenieurwesen	
HS Niederrhein, Krefeld	
Wilhelm-Büchner HS, Pfungstadt	03/2018
GRS, Köln	
WIB, Dennheritz	
RONAL AG, Härklingen, Schweiz	02/2018
Ingenieurbüro Leipert, Riegelsberg	
AIXPROCESS, Aachen	
KRONES, Neutraubling	
Doosan Lentjes, Ratingen	01/2018