User's Guide

for

LibHuAirProp

Library of Psychrometric, Thermodynamic,
and Transport Properties
for *Real* Humid Air, Steam, Water, and Ice
I-P & SI Units

FluidEXL for Excel®

Version 6.0

Based on ASHRAE Research Project RP-1485
and PTB-CP-3 Report

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Prepared by
THERMO FLUID PROP
www.thermofluidprop.com

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ISBN 978-1-933742-74-8

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®, EES®, LabVIEW™, DYMOLA®, or SimulationX®?

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

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)
December 11, 2009 (revised Table C.2)

VOLUME 15, NUMBER 5   HVAC&R RESEARCH   SEPTEMBER 2009

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

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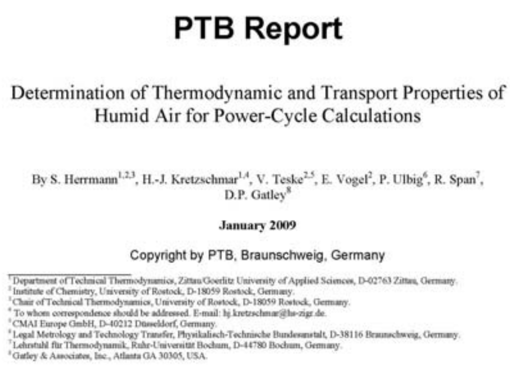
Received February 14, 2009; accepted May 6, 2009

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 properties of moist air from the PTB Report PTB-CP-3 and the related paper in the Journal of Engineering for Gas Turbines and Power



PTB Report

Determination of Thermodynamic and Transport Properties of Humid Air for Power-Cycle Calculations

By S. Herrmann[1,2,3], H.-J. Kretzschmar[1,4], V. Teske[2,5], E. Vogel[2], P. Ulbig[6], R. Span[7], D.P. Gatley[8]

January 2009

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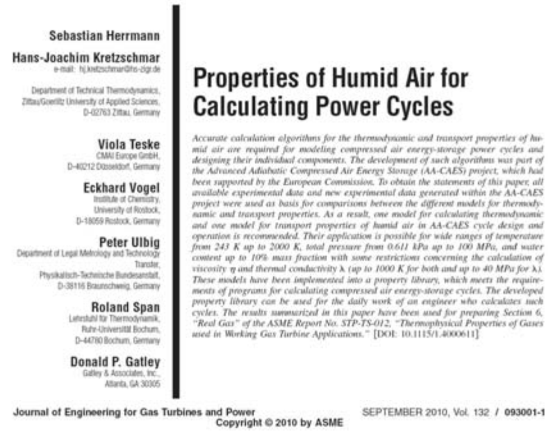

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Properties of Humid Air for Calculating Power Cycles

Accurate calculation algorithms for the thermodynamic and transport properties of humid air are required for modeling compressed air energy-storage power cycles and designing their individual components. The development of such algorithms was part of the Advanced Adiabatic Compressed Air Energy Storage (AA-CAES) project, which had been supported by the European Commission. To obtain the statements of this paper, all available experimental data and new experimental data generated within the AA-CAES project were used as basis for comparisons between the different models for thermodynamic and transport properties. As a result, one model for calculating thermodynamic and one model for transport properties of humid air in AA-CAES cycle design and operation is recommended. Their application is possible for wide ranges of temperature from 243 K up to 2000 K, total pressure from 0.611 kPa up to 100 MPa, and water content up to 10% mass fraction with some restrictions concerning the calculation of viscosity η and thermal conductivity λ (up to 1000 K for both and up to 40 MPa for λ). These models have been implemented into a property library, which meets the requirements of programs for calculating compressed air energy-storage cycles. The developed property library can be used for the daily work of an engineer who calculates such cycles. The results summarized in this paper have been used for preparing Section 6, "Real Gas" of the ASME Report No. STP-TS-012, "Thermophysical Properties of Gases used in Working Gas Turbine Applications." [DOI: 10.1115/1.4000611]

Journal of Engineering for Gas Turbines and Power SEPTEMBER 2010, Vol. 132 / 093001-1
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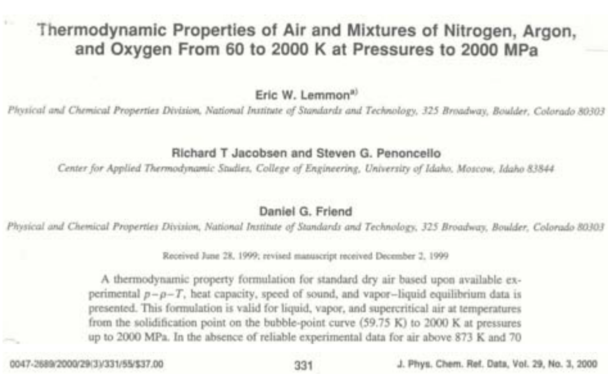
Properties of dry air from the NIST Reference Equation of *Lemmon et al.* and properties of steam, water, and ice from the Industrial Formulation IAPWS-IF97, the Scientific Formulation IAPWS-95, and other current IAPWS formulations



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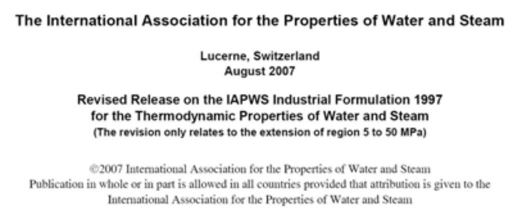
Received June 28, 1999; revised manuscript received December 2, 1999

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

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)

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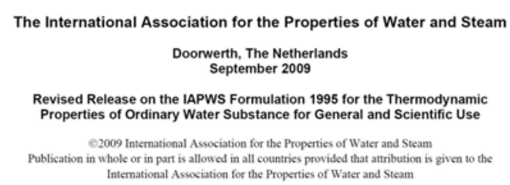

The International Association for the Properties of Water and Steam

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

Contents

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0 Package Contents

0.1 Add-In for 32-bit version of Microsoft Office®

The following ZIP file is delivered for your computer running a 32-bit version of Microsoft Office®.

ZIP file "CD_FluidEXL_ASHRAE_LibHuAirProp.zip" for Excel®

The ZIP file contains the following files:

FluidEXL_ASHRAE_LibHuAirProp_Setup.exe	Installation program for the FluidEXL*Graphics* Add-In for use in Excel®
FluidEXL_ASHRAE_LibHuAirProp_ Users_Guide.pdf	User's Guide

0.2 Add-Ins for 64-bit version of Microsoft Office®

The following ZIP file is delivered for your computer running a 64-bit version of Microsoft Office®.

ZIP file "CD_FluidEXL_ASHRAE_LibHuAirProp_x64.zip" for Excel®

The ZIP file contains the following files and folders:

FluidEXL_ASHRAE_LibHuAirProp_Users_Guide.pdf	User's Guide
FluidEXL_ASHRAE_LibHuAirProp_64_Setup.msi	Self-extracting and self-installing program
setup.exe	Installation program for the FluidEXL*Graphics* Add-In for use in Excel®
vcredist_x64	Folder containing the "Microsoft Visual C++ 2010 x64 Redistributable Pack"
WindowsInstaller3_1	Folder containing the "Microsoft Windows Installer"

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
$a = f(p,t,W)$	a_ptW_HAP_IP	Thermal diffusivity	ft²/s	3/2
$\alpha_p = f(p,t,W)$	alphap_ptW_HAP_IP	Relative pressure coefficient	1/°R	3/3
$\beta_p = f(p,t,W)$	betap_ptW_HAP_IP	Isothermal stress coefficient	lb/ft³	3/4
$c = f(p,t,W)$	c_ptW_HAP_IP	Speed of sound	ft/s	3/5
$c_p = f(p,t,W)$	cp_ptW_HAP_IP	Specific isobaric heat capacity	Btu/(lb·°R)	3/6
$c_v = f(p,t,W)$	cv_ptW_HAP_IP	Specific isochoric heat capacity	Btu/(lb·°R)	3/7
$f = f(p,t)$	f_pt_HAP_IP	Enhancement factor (decimal ratio)	-	3/8
$h = f(p,t,W)$	h_ptW_HAP_IP	Air-specific enthalpy	Btu/lb_a	3/9
$\eta = f(p,t,W)$	Eta_ptW_HAP_IP	Dynamic viscosity	lb·s/ft²	3/10
$\kappa = f(p,t,W)$	Kappa_ptW_HAP_IP	Isentropic exponent	-	3/11
$\lambda = f(p,t,W)$	Lambda_ptW_HAP_IP	Thermal conductivity	Btu/(h·ft·°R)	3/12
$\nu = f(p,t,W)$	Ny_ptW_HAP_IP	Kinematic viscosity	ft²/s	3/13
$p = f(t,s,W)$	p_tsW_HAP_IP	Pressure of humid air	psi	3/14
$p = f(z_{ele})$	p_zele_HAP_IP	Pressure of humid air from elevation	psi	3/15
$p_{Air} = f(p,t,W)$	pAIR_ptW_HAP_IP	Partial pressure of dry air in moist air	psi	3/16
$p_{H2O} = f(p,t,W)$	pH2O_ptW_HAP_IP	Partial pressure of water vapor in moist air	psi	3/17
$p_{H2Os} = f(p,t)$	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·°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
$W = f(p,t,t_{wb})$	W_pttwb_HAP_IP	Humidity ratio from total pressure, (dry bulb) temperature, and wet-bulb temperature	lb_w/lb_a	3/37
$W_s = f(p,t)$	Ws_pt_HAP_IP	Saturation humidity ratio	lb_w/lb_a	3/38
$\xi_{Air} = f(W)$	XiAir_W_HAP_IP	Mass fraction of dry air in moist air	lb_a/lb	3/39
$\xi_{H2O} = f(W)$	XiH2O_W_HAP_IP	Mass fraction of water vapor in moist air	lb_w/lb	3/40
$Z = f(p,t,W)$	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	ft^3/lb	3/51
$v_{liq,s} = f(t)$	vliqs_t_97_IP	Specific volume of saturated liquid water	ft^3/lb	3/52
$v_{vap,s} = f(t)$	vvaps_t_97_IP	Specific volume of saturated water vapor	ft^3/lb	3/53

Range of Validity

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

Units

Symbol	Quantity	Unit
p	Pressure	psi
t	Temperature	°F

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	ft^3/lb	3/63
$v_{vap,sub} = f(t)$	vvapsub_t_95_IP	Specific volume of saturated water vapor	ft^3/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	$\frac{a_{IP}}{\frac{ft^2}{s}} = \frac{a_{SI}}{\frac{m^2}{s}} \times 10.76391042$	$\frac{a_{SI}}{\frac{m^2}{s}} = \frac{a_{IP}}{\frac{ft^2}{s}} \times 0.0929304$	m²/s	ft²/s
Relative pressure coefficient	α_p	$\frac{\alpha_{p,IP}}{\frac{1}{°R}} = \frac{\alpha_{p,SI}}{\frac{1}{K}} \times \frac{9}{5}$	$\frac{\alpha_{p,SI}}{\frac{1}{K}} = \frac{\alpha_{p,IP}}{\frac{1}{°R}} \times \frac{5}{9}$	1/K	1/°R
Isothermal stress coefficient	β_p	$\frac{\beta_{p,IP}}{\frac{lb}{ft^3}} = \frac{\beta_{p,SI}}{\frac{kg}{m^3}} \times 0.062428$	$\frac{\beta_{p,SI}}{\frac{kg}{m^3}} = \frac{\beta_{p,IP}}{\frac{lb}{ft^3}} \times 16.018463$	kg/m³	lb/ft³
Speed of sound	c	$\frac{c_{IP}}{\frac{ft}{s}} = \frac{c_{SI}}{\frac{m}{s}} \times 3.2808399$	$\frac{c_{SI}}{\frac{m}{s}} = \frac{c_{IP}}{\frac{ft}{s}} \times 0.3048$	m/s	ft/s
Specific isobaric heat capacity	c_p	$\frac{c_{p,IP}}{\frac{Btu}{lb\ °R}} = \frac{c_{p,SI}}{\frac{kJ}{kg\ K}} \times 0.2388459$	$\frac{c_{p,SI}}{\frac{kJ}{kg\ K}} = \frac{c_{p,IP}}{\frac{Btu}{lb\ °R}} \times 4.1868$	kJ/(kg·K)	Btu/(lb·°R)
Specific isochoric heat capacity	c_v	$\frac{c_{v,IP}}{\frac{Btu}{lb\ °R}} = \frac{c_{v,SI}}{\frac{kJ}{kg\ K}} \times 0.2388459$	$\frac{c_{v,SI}}{\frac{kJ}{kg\ K}} = \frac{c_{v,IP}}{\frac{Btu}{lb\ °R}} \times 4.1868$	kJ/(kg·K)	Btu/(lb·°R)
Dynamic viscosity	η	$\frac{\eta_{IP}}{\frac{lb\ s}{ft^2}} = \frac{\eta_{SI}}{\frac{Pa}{s}} \times 0.02088543$	$\frac{\eta_{SI}}{\frac{Pa}{s}} = \frac{\eta_{IP}}{\frac{lb\ s}{ft^2}} \times 47.880259$	Pa·s	lb·s/ft²
Enhancement factor	f	$f_{IP} = f_{SI}$	$f_{SI} = f_{IP}$	-	-

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·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	$\frac{s_{IP}}{\frac{Btu}{lb_a\ °R}} = \frac{s_{SI}}{\frac{kJ}{kg_a\ K}} \times 0.23884589$	$\frac{s_{SI}}{\frac{kJ}{kg_a\ K}} = \frac{s_{IP}}{\frac{Btu}{lb_a\ °R}} \times 4.1868$	kJ/(kg$_a$·K)	Btu/(lb$_a$·°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
Air-specific volume (moist air)	v	$\frac{v_{IP}}{\frac{ft^3}{lb_a}} = \frac{v_{SI}}{\frac{m^3}{kg_a}} \times 16.018453$	$\frac{v_{SI}}{\frac{m^3}{kg_a}} = \frac{v_{IP}}{\frac{ft^3}{lb_a}} \times 0.062428$	m³/kg$_a$	ft³/lb$_a$
Specific volume (water, water vapor, ice)	v_w	$\frac{v_{IP}}{\frac{ft^3}{lb}} = \frac{v_{SI}}{\frac{m^3}{kg}} \times 16.018453$	$\frac{v_{SI}}{\frac{m^3}{kg}} = \frac{v_{IP}}{\frac{ft^3}{lb}} \times 0.062428$	m³/kg	ft³/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]
- the calculation of the second and third molar virial coefficients B_{ww} and C_{www} for water and steam from IAPWS-95 [5], [6]
- 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.

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 $p_{subl}^{08}(t)$ [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.

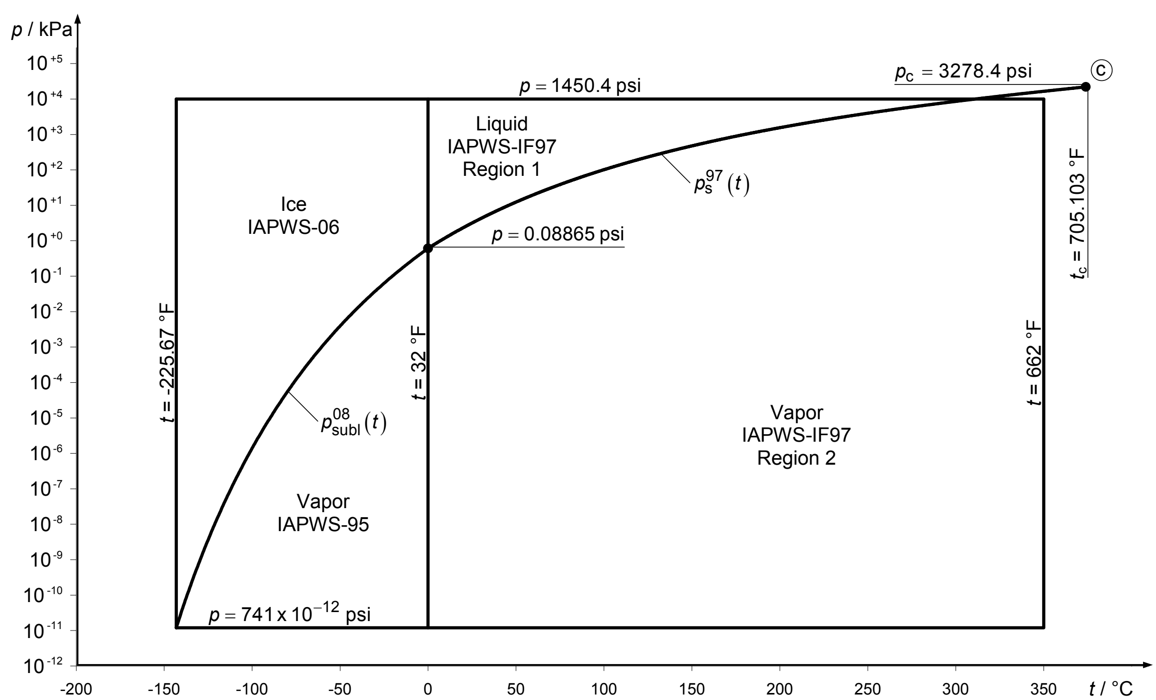

Figure 1: *p-T* diagram with used IAPWS formulations for steam, water, and ice.

2 Add-In FluidEXL*Graphics* for Excel® for ASHRAE-LibHuAirProp-IP

2.1 Installing FluidEXL*Graphics* for Excel®

The FluidEXL*Graphics* Add-In has been developed to calculate thermophysical properties in Excel® more conveniently. Within Excel®, it enables the direct call of functions relating to real moist air, steam, water, and ice from the ASHRAE-LibHuAirProp-IP property library.

2.1.1 Installing FluidEXL*Graphics* including LibHuAirProp

Installing FluidEXL*Graphics* including LibHuAirProp for 32-bit Office®

In this section, the installation of FluidEXL*Graphics* and both LibHuAirProp_IP and LibHuAirProp_SI is described.
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_FluidEXL_ASHRAE_LibHuAirProp.zip," you will see the folder

CD_FluidEXL_ASHRAE_LibHuAirProp

in your Windows Explorer®, Norton Commander®, or any other similar program you may be using.

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

Within this folder you will see the following files:

FluidEXL_ASHRAE_LibHuAirProp_Users_Guide.pdf
FluidEXL_ASHRAE_LibHuAirProp_Setup.exe.

In order to run the installation of FluidEXL*Graphics* including the ASHRAE-LibHuAirProp-IP property library, double-click on the file

FluidEXL_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.

In the following dialog box, "Choose Destination Location," the default path offered automatically for the installation of FluidEXL*Graphics* is

C:\Program Files\FluidEXL_Graphics_Eng.

By clicking the "Browse…" button, you can change the installation directory before installation (see figure below).

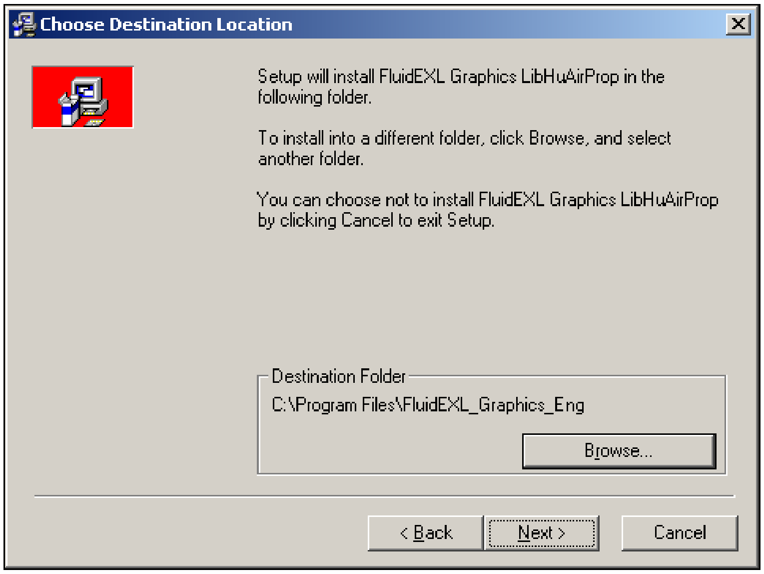

Figure 2.1.1: "Choose Destination Location"

Finally, click on "Next >" to continue installation; click "Next >" again in the "Start Installation" window which follows in order to start the installation of FluidEXL*Graphics*.

After FluidEXL*Graphics* has been installed, you will see the sentence "FluidEXL Graphics LibHuAirProp has been successfully installed." Confirm this by clicking the "Finish" button.

The installation of FluidEXL*Graphics* has been completed.

During the installation process the following files will have been copied into the chosen destination folder, the standard being
C:\Program Files\FluidEXL_Graphics_Eng:

advapi32.dll
Dformd.dll
Dforrt.dll
FluidEXL_Graphics_Eng.xla
INSTALL_EXL.LOG
LC.dll
LCKCE.dll
LibHuAirProp_IP.dll
LibHuAirProp_IP.hlp
LibHuAirProp_SI.dll
LibHuAirProp_SI.hlp
msvcp60.dll
msvcrt.dll
UNWISE.EXE.

Installing FluidEXL*Graphics* including LibHuAirProp for 64-bit Office®

In this section, the installation of FluidEXL*Graphics* and both LibHuAirProp_IP and LibHuAirProp_SI is described.

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_FluidEXL_ASHRAE_LibHuAirProp.zip," you will see the folder

CD_FluidEXL_ASHRAE_LibHuAirProp

in your Windows Explorer®, Norton Commander®, or any other similar program you may be using.

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

Within this folder you will see the following files:

FluidEXL_ASHRAE_LibHuAirProp_Users_Guide.pdf
FluidEXL_ASHRAE_LibHuAirProp_64_Setup.msi
setup.exe

and the folders

vcredist_x64
WindowsInstaller3_1.

In order to run the installation of FluidEXL*Graphics* including the ASHRAE-LibHuAirProp-IP and ASHRAE-LibHuAirProp-SI property library, double-click on the file

setup.exe.

If the "Microsoft Visual C++ 2010 x64 Redistributable Pack" is not running on your computer yet, installation will start with a window noting that the "Visual C++ 2010 runtime library (x64)" will be installed on your machine (see Figure 2.1.2).

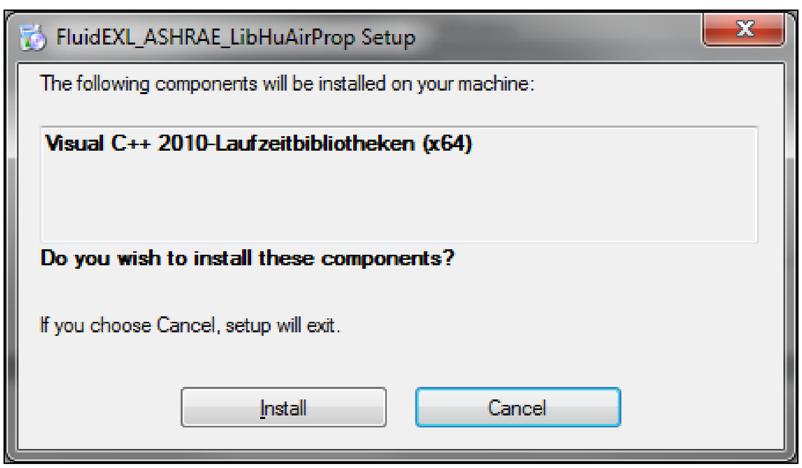

Figure 2.1.2: Installing the "Visual C++ 2010 runtime library (x64)"

Click on "Install" to continue.

Note.

If there is a newer version of "Microsoft Visual C++ 2010 x64 Redistributable" package installed on your computer than the one provided in this installation setup.exe will stop and is followed by an error message. In this case please start the installation again by double-clicking the file "FluidEXL_LibHuAirProp_64_Setup.msi" and skip the next three steps described in the User's Guide.

In the following window you are required to accept the Microsoft® license terms to install the "Microsoft Visual C++ 2010 x64 Redistributable Pack" by ticking the box next to "I have read and accept the license terms" (see Figure 2.1.3).

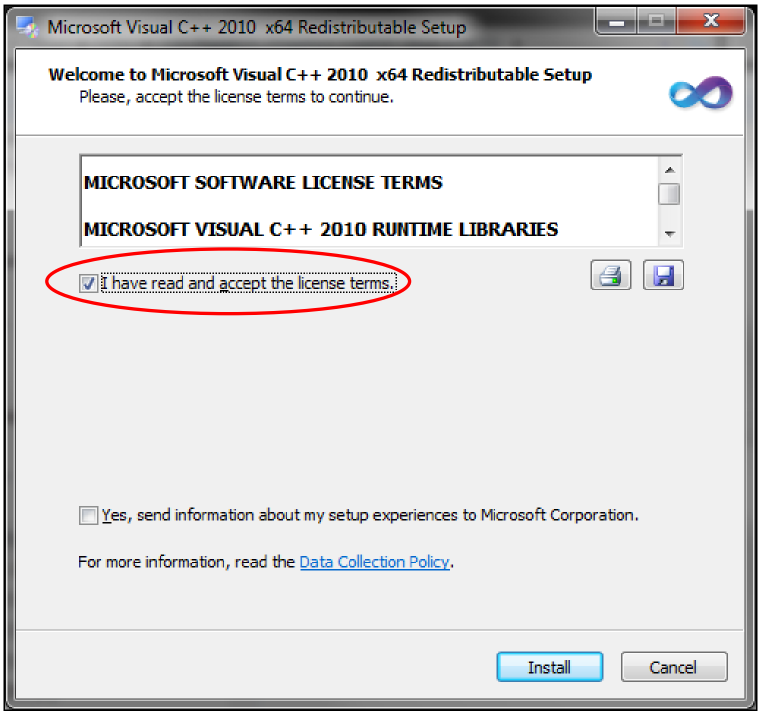

Figure 2.1.3: Accepting the license terms

Now click on "Install" to continue installation.

After the "Microsoft Visual C++ 2010 x64 Redistributable Pack" has been installed, you will see the sentence "Microsoft Visual C++ 2010 x64 Redistributable has been installed." Confirm this by clicking "Finish."

Now the installation of FluidEXL_ASHRAE_LibHuAirProp starts with a window noting that the installer will guide you through the installation. Click the "Next >" button to continue.

In the following dialog box, "Select Installation Folder," the default path offered automatically for the installation of FluidEXL*Graphics* is

C:\Program Files\FluidEXL_Graphics_Eng.

By clicking the "Browse…" button, you can change the installation directory before installation (see Figure 2.1.4).

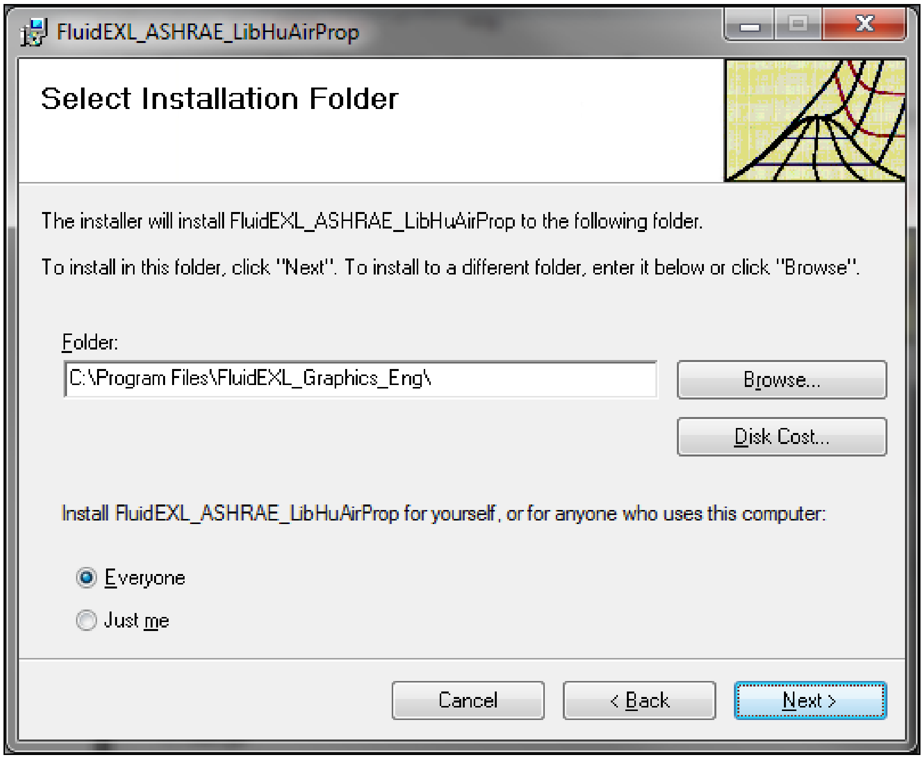

Figure 2.1.4: Choosing the installation folder

Finally, click on "Next >" to continue installation; click "Next >" again in the "Confirm Installation" window which follows in order to start the installation of FluidEXL*Graphics*.

After FluidEXL*Graphics* has been installed, you will see the sentence "FluidEXL_ASHRAE_LibHuAirProp has been successfully installed." Confirm this by clicking the "Close" button.
The installation of FluidEXL*Graphics* has been completed.

During the installation process the following files will have been copied into the chosen destination folder, the standard being
C:\Program Files\FluidEXL_Graphics_Eng:

capt_ico_big.ico	LibHuAirProp_SI.dll
FluidEXL_Graphics_Eng.xla	LibHuAirProp_SI.hlp
LC.dll	libifcoremd.dll
LCKCE.dll	libiomp5md.dll
LibHuAirProp_IP.dll	libmmd.dll
LibHuAirProp_IP.hlp.	

In addition, the two subdirectories \FORMULATION97 and \FLuft were created in the destination folder.

2.1.2 Registering FluidEXL*Graphics* as Add-In in Excel®

Registering FluidEXL*Graphics* as Add-In in Excel® versions 2003 or earlier

After the installation of FluidEXL*Graphics*, the program must be registered as an Add-In in Excel®. In order to do so, start Excel® and carry out the following steps:

- Click "Tools" in the upper menu bar of Excel.
- Here, click on "Add-Ins..." in the menu.

After a short delay the "Add-Ins" dialog box will appear.

- Click "Browse..."
- In the following dialog box, choose your chosen destination folder (the standard being

  C:\Program Files\FluidEXL_Graphics_Eng)

  here select "FluidEXL_Graphics_Eng.xla" and afterwards click "OK".
- Now, the entry "FluidEXL Graphics Eng" will appear in the Add-Ins list.

Note:

As long as the check box next to the file name

"FluidEXL Graphics Eng"

is checked, this Add-In will be loaded automatically every time you start Excel until you unmark the box by clicking on it again.

- In order to register FluidEXL*Graphics* as an Add-In, click "OK" in the "Add-Ins" dialog box.

Now, the new FluidEXL*Graphics* menu bar will appear in the upper menu area of your Excel screen, marked with a red circle in Figure 2.1.5:

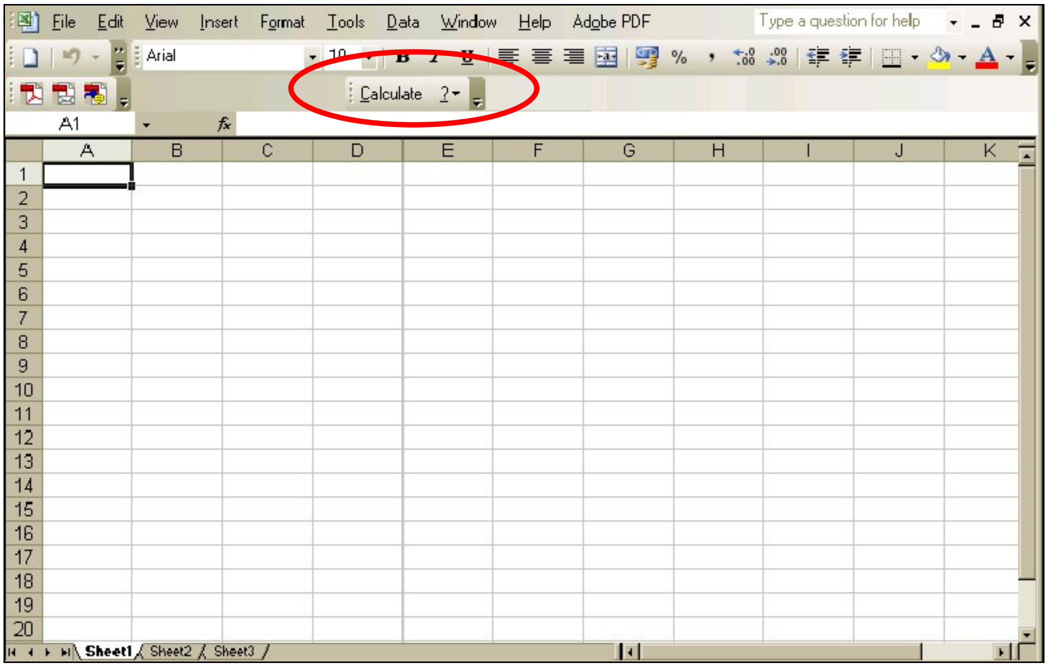

Figure 2.1.5: Menu bar of FluidEXL*Graphics*

From within Excel® you can now select the "ASHRAE-LibHuAirProp-IP" DLL library property functions for moist air via this menu bar (see part 2.1.5).

Registering FluidEXL*Graphics* as an Add-In in Excel® 2007 (or later versions)

After installation in Windows®, FluidEXL*Graphics* must be registered in Excel® versions 2007 and later as an Add-In. To do this, start Excel® and carry out the following steps:

- Click the Windows Office® button in the upper left hand corner of Excel®
- Click on the "Excel Options" button in the menu which then appears (see figure below)

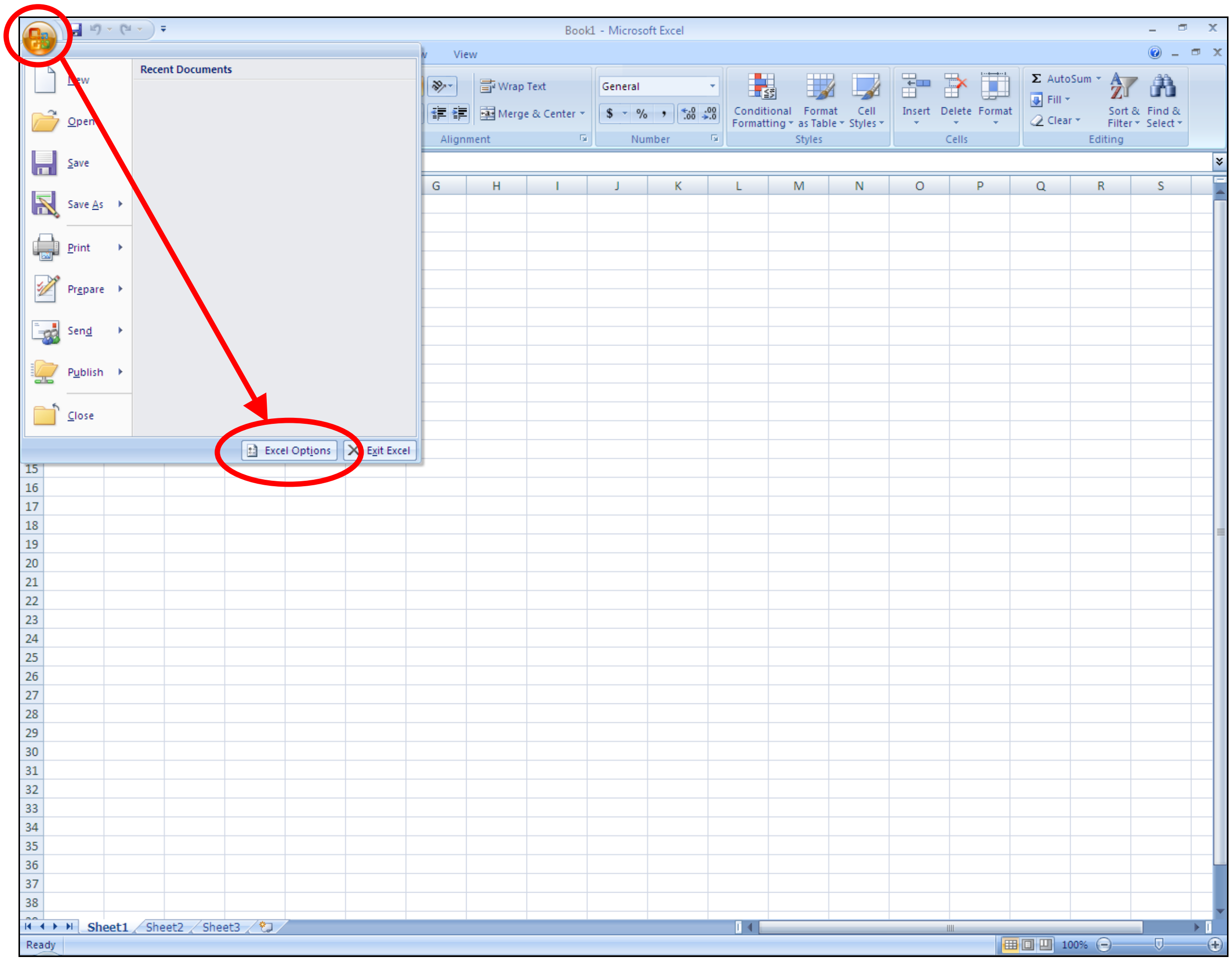

Figure 2.1.6: Registering FluidEXL*Graphics* as Add-In in Excel® 2007

- Click on "Add-Ins" in the next menu

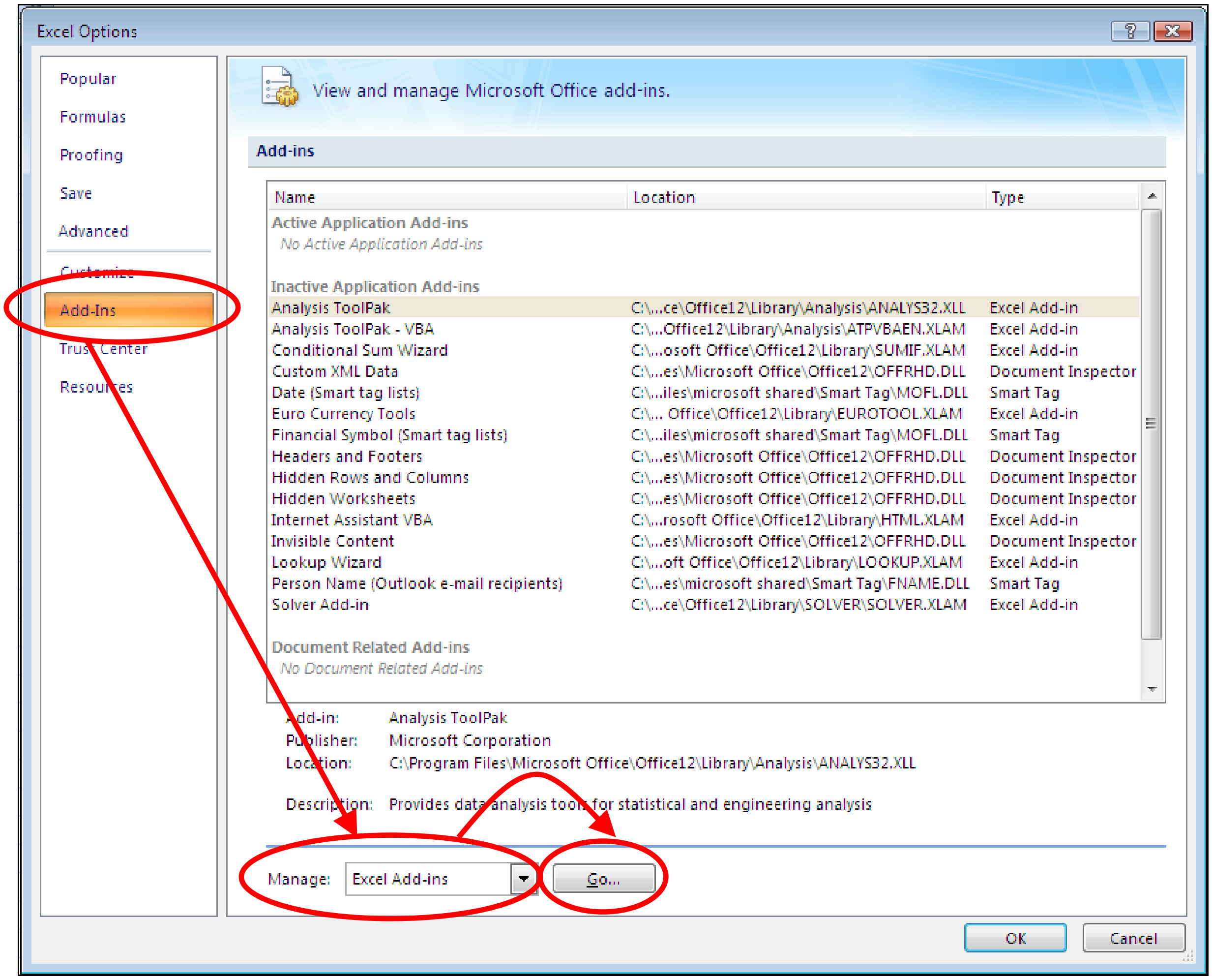

Figure 2.1.7: Dialog window "Add-Ins"

- Should it not be shown in the list automatically, select "Excel Add-ins" (found next to "Manage:" in the lower area of the menu)
- Then click the "Go…" button
- Click "Browse" in the following window and locate the destination folder, generally

  C:\Program Files\FluidEXL_Graphics_Eng;

  within that folder click on the file named "FluidEXL_Graphics_Eng.xla" and then hit "OK."

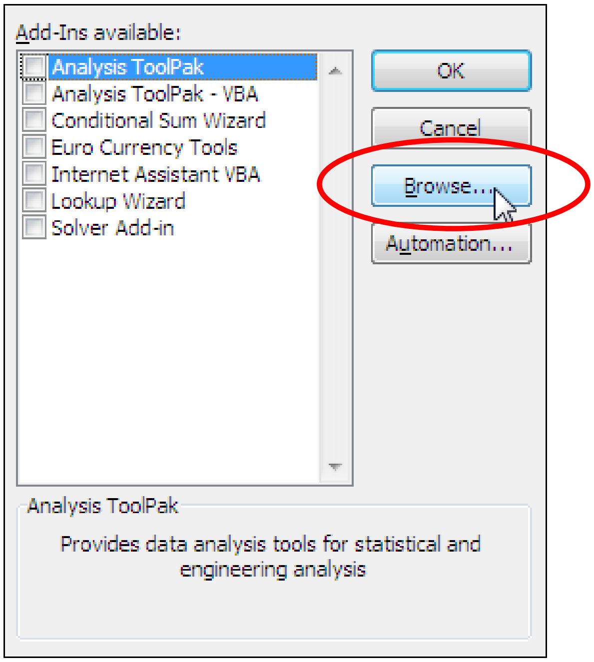

Figure 2.1.8: Dialog window "Add-Ins available"

- Now, "FluidEXL Graphics Eng" will be shown in your list of Add-Ins.
  (If a check-mark is situated in the box next to the name "FluidEXL Graphics", this Add-In will automatically be loaded whenever Excel starts. This will continue to occur unless the check-mark is removed from the box by clicking on it.)

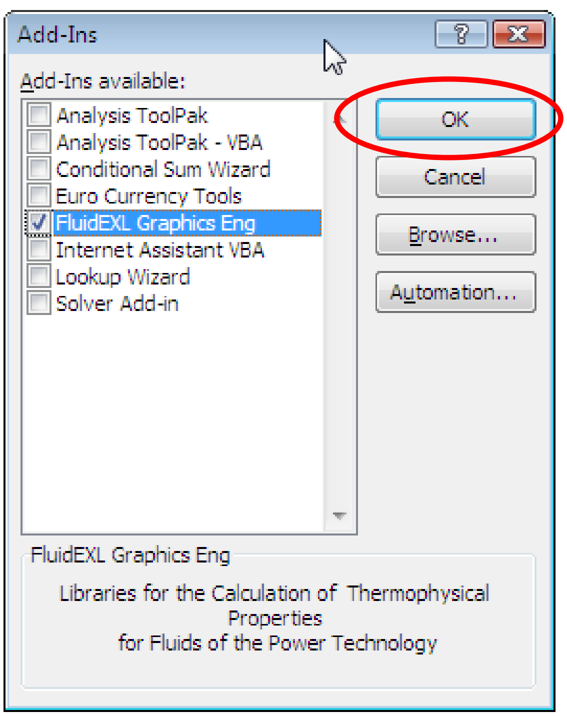

Figure 2.1.9: Dialog window "Add-Ins"

- In order to register the Add-In, click the "OK" button in the "Add-Ins" window.

In order to use FluidEXL*Graphics* in the following example, click on the menu item "Add-Ins," shown in the next figure.

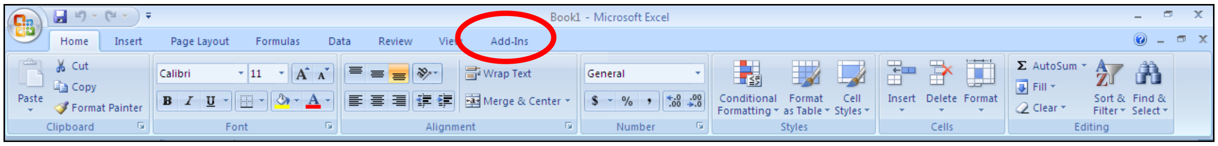

Figure 2.1.10: Menu item "Add-Ins"

In the upper menu region of Excel®, the FluidEXL*Graphics* menu bar will appear as indicated by the red circle in the next figure.

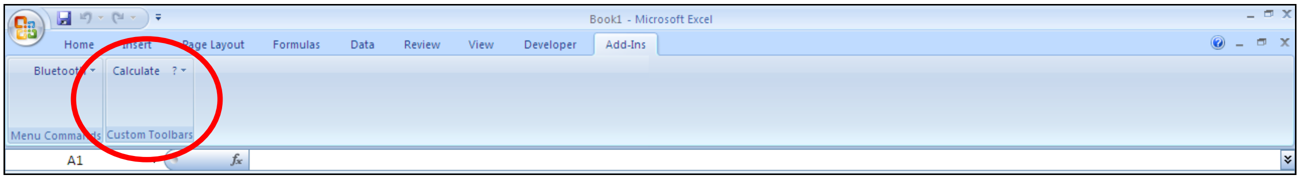

Figure 2.1.11: FluidEXL*Graphics* menu bar

Installation of FluidEXL*Graphics* in Excel (versions 2007 and later) is now finished. FluidEXL*Graphics* can be used analogous to the description for using with earlier Excel versions.

2.1.3 The FluidEXL*Graphics* Help System

As mentioned earlier, FluidEXL*Graphics* also provides detailed online help functions.
If you are running Windows Vista or Windows 7, please note the paragraph "Using the FluidEXL*Graphics* Online-Help in Windows Vista or Windows 7."
For general information in Excel®:

- Click on "?" and then "Help" in the FluidEXL*Graphics* menu bar.

Information on individual property functions may be accessed via the following steps:

- Click "Calculate" in the FluidEXL*Graphics* menu bar.
- Select the "ASHRAE-LibHuAirProp-IP" library under "Or select a category:" in the "Insert Function" window which will appear.
- Click the "Help on this function" button in the lower left-hand edge of the "Insert Function" window.
- If the "Office Assistant" is active, first double-click "Help on this feature" and in the next menu click "Help on selected function."

If the "LibHuAirProp_IP.hlp" function help cannot be found, you will be asked whether you want to look for it yourself – answer with "Yes." Click on the "LibHuAirProp_IP.hlp" file in the installation menu of FluidEXL*Graphics* in the window which is opened, the standard being

C:\Program Files\FluidEXL_Graphics_Eng

and click "Yes" in order to complete the search.

Using the FluidEXL*Graphics* Online Help in Windows Vista or Windows 7

If you are running Windows Vista or Windows 7 on your computer, you might not be able to open Help files. To view these files you have to install the Microsoft® Windows Help program which is provided by Microsoft®. Please carry out the following steps in order to download and install the Windows Help program.

Open Microsoft Internet Explorer® and go to the following address:

http://support.microsoft.com/kb/917607/

You will see the following web page:

Figure 2.1.12: Microsoft® Support web page

Scroll down until you see the headline "Resolution." Here you can see the bold hint:

"Download the appropriate version of Windows Help program (WinHlp32.exe), depending on the operating system that you are using:"

The following description relates to Windows® 7. The procedure is analogous for Windows® Vista.

Click on the link "Windows Help program (WinHlp32.exe) for Windows 7" (see Figure 2.1.13).

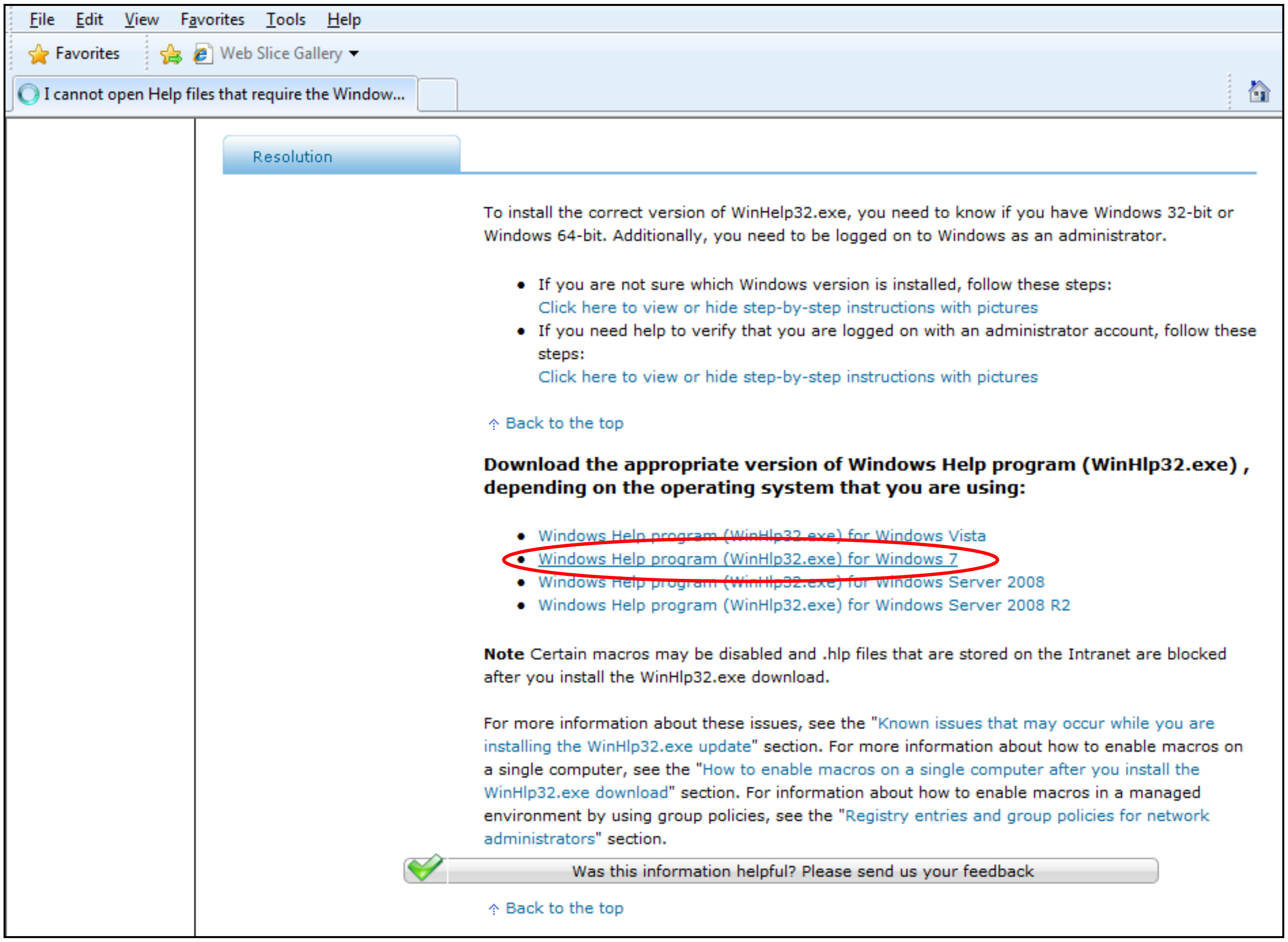

Figure 2.1.13: Selecting your Windows version

You will be forwarded to the Microsoft Download Center where you can download the Microsoft Windows Help program.

First, a validation of your Windows License is required.

To do this click on the "Continue" button (see Figure 2.1.14).

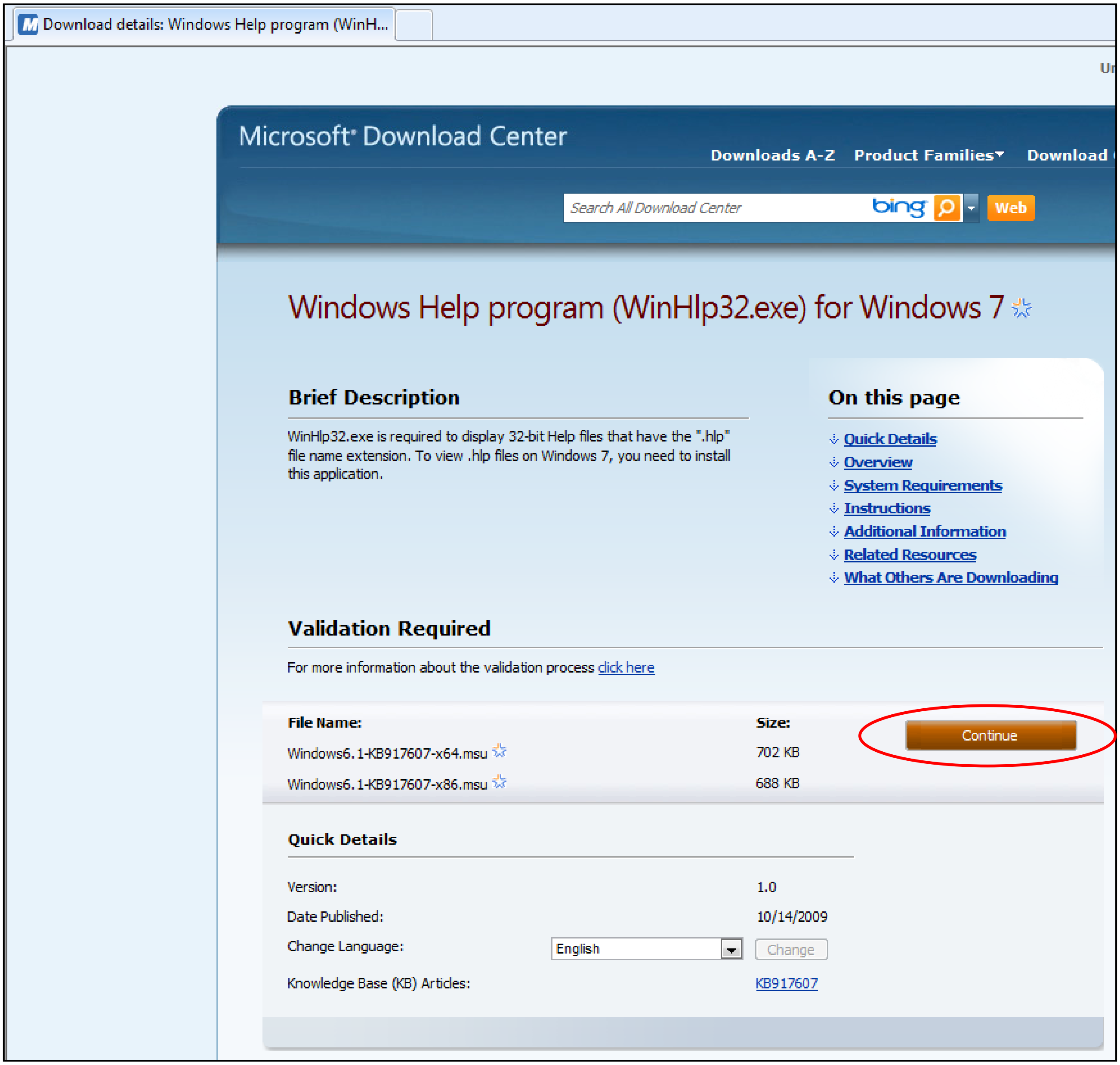

Figure 2.1.14: Microsoft® Download Center

You will be forwarded to a web page with instructions on how to install the Genuine Windows Validation Component.

At the top of your Windows Internet Explorer you will see a yellow information bar. Right-click this bar and select "Install ActiveX Control" in the context menu (see Figure 2.1.15).

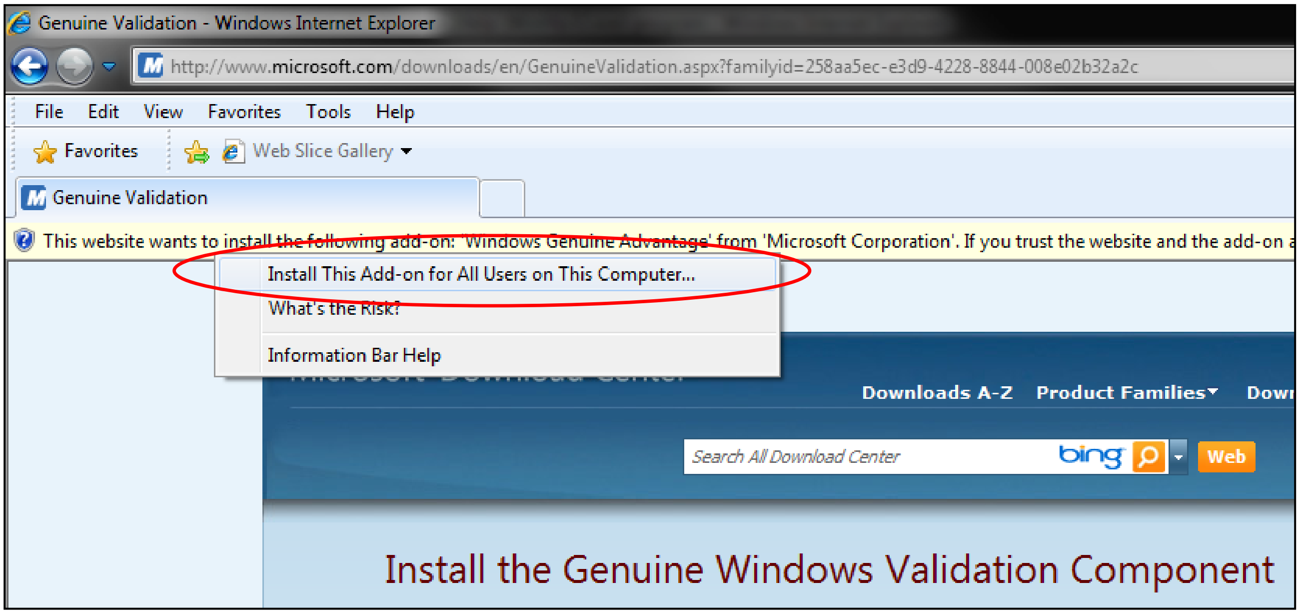

Figure 2.1.5 Installing the Genuine Windows Validation Component

A dialog window appears in which you will be asked if you want to install the software. Click the "Install" button to continue (see Figure 2.1.16).

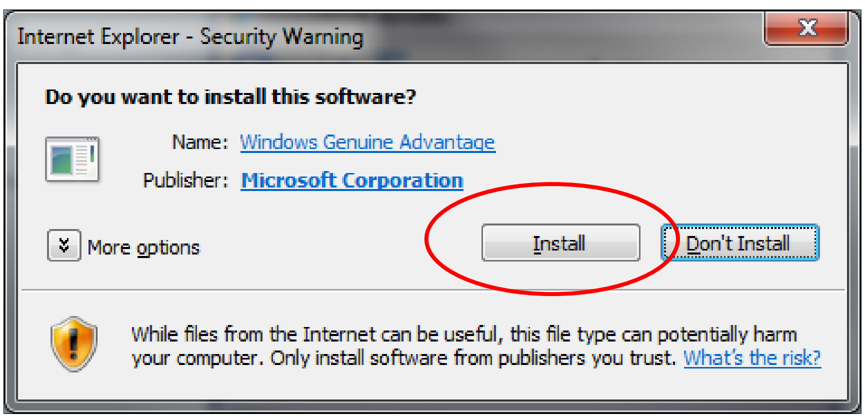

Figure 2.1.16: Internet Explorer – Security Warning

After the validation has been carried out you will be able to download the appropriate version of Windows Help program (see Figure 2.1.17).

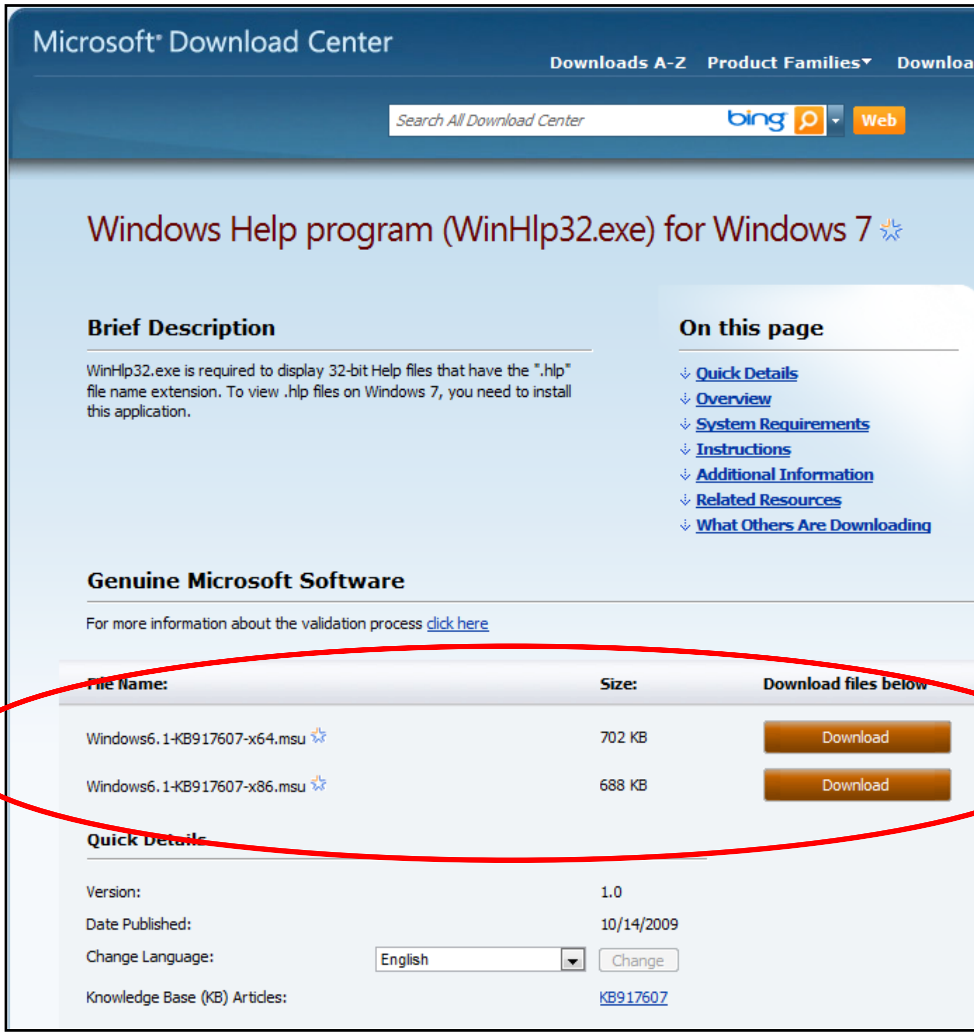

Figure 2.1.17: Downloading the Windows Help program

To download and install the correct file you need to know which Windows version (32-bit or 64-bit) you are running on your computer.

If you are running a 64-bit operating system, please download the file

Windows6.1-KB917607-x64.msu.

If you are running a 32-bit operating system, please download the file

Windows6.1-KB917607-x86.msu.

In order to run the installation of the Windows Help program double-click the file you have just downloaded on your computer:

Windows6.1-KB917607-x64.msu (for 64-bit operating system)
Windows6.1-KB917607-x86.msu. (for 32-bit operating system).

Installation starts with a window searching for updates on your computer. After the program has finished searching you may see the following window.

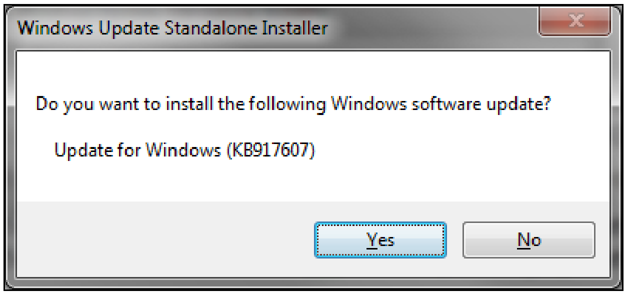

Figure 2.1.18: Windows Update Standalone Installer

In this case, the installation can be continued by clicking the "Yes" button.
(If you have already installed this update, you will see the message "Update for Windows (KB917607) is already installed on this computer.")

In the next window you have to accept the Microsoft license terms before installing the update by clicking on "I Accept" (see Figure 2.1.19)

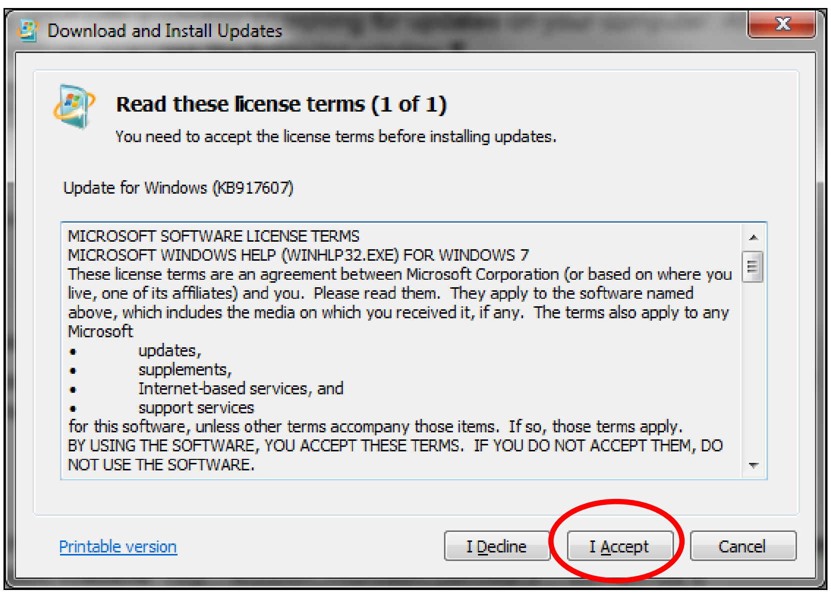

Figure 2.1.19: Windows License Terms

Installation starts once you have clicked the "I Accept" button (see Figure 2.1.20).

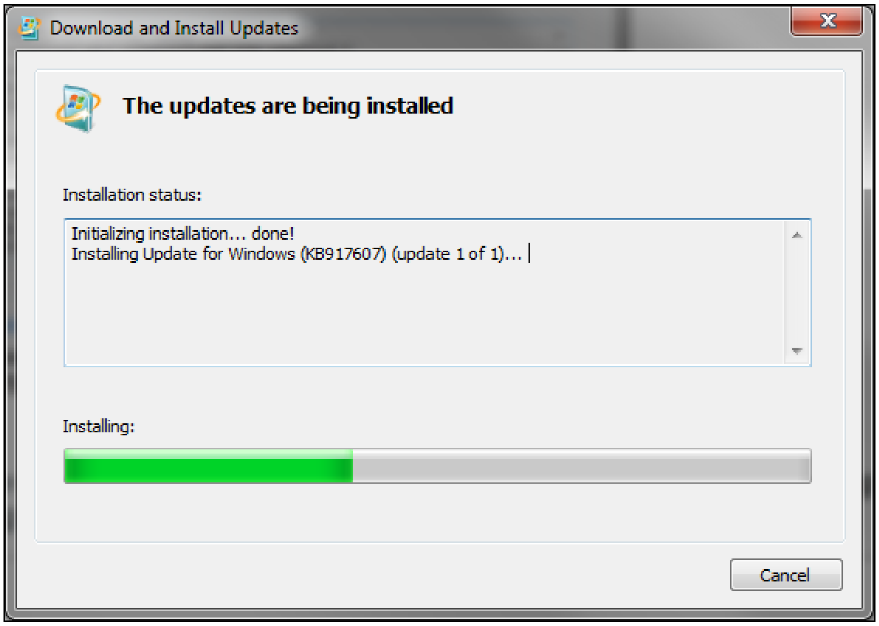

Figure 2.1.20: Installation process

After the Windows Help program has been installed, the notification "Installation complete" will appear. Confirm this by clicking the "Close" button.

The installation of the Windows Help program has been completed and you will now be able to open the Help files.

2.2 Licensing the LibHuAirProp Property Library

The licensing procedure must be carried out when Excel® starts up and a FluidEXL*Graphics* prompt message appears. In this case, you will see the "License Information" window for LibHuAirProp (see figure below).

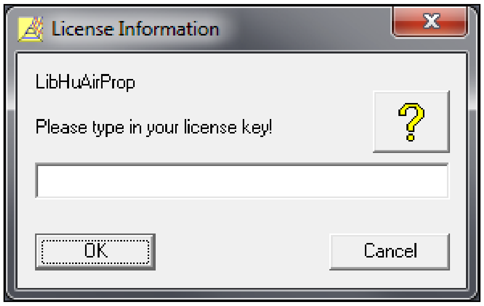

Figure 2.2.21: "License Information" window

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. Then the following window will appear:

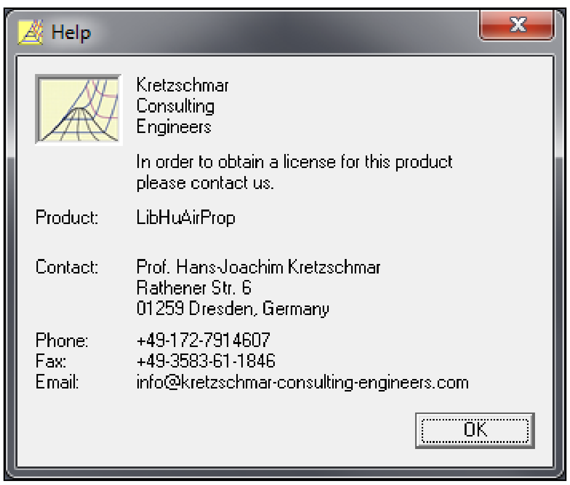

Figure 2.2.22: "Help" window

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

The "License Information" window will appear every time you start Excel® unless you uninstall FluidEXL*Graphics* according to the description in section 2.4 of this User's Guide.

Should you not wish to license the LibHuAirProp property library, you have to delete the files

LibHuAirProp_IP.dll	LibHuAirProp_SI.dll
LibHuAirProp_IP.hlp	LibHuAirProp_SI.hlp

in the installation folder of FluidEXL*Graphics* (the standard being

C:\Program Files\FluidEXL_Graphics_Eng)

using an appropriate program such as Explorer® or Norton Commander®.

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*)

We will now calculate, step by step, the air-specific enthalpy *h* of real moist air as a function of total pressure *p*, temperature *t* and humidity ratio *W*, using FluidEXL*Graphics*. The following description relates to Excel® 2003. The use of FluidEXL*Graphics* here is analogous to the description for using it with earlier or later Excel® versions.

Please carry out the following steps:

- Start Excel®
- Enter the value for *p* in psi into a cell
  (Range of validity: p = 0.00145 … 1450.4 psi

  ⇒ e.g.: Enter the value 14.6959 into cell A2
- Enter the value for *t* in °F into a cell
  (Range of validity: t = –226.67 ... 662 °F)

  ⇒ e.g.: Enter the value 68 into cell B2
- Enter the value for *W* in lb_w/lb_a (*lb water* per *lb dry air*) into a cell
  (Range of validity: W = 0 … 10 lb_w/lb_a)

  ⇒ e.g.: Enter the value 0.01 into cell C2
- Click the cell in which the air-specific enthalpy *h* in Btu/lb_a is to be displayed
  ⇒ e.g.: Click cell D2
- Click "Calculate" in the FluidEXL*Graphics* menu bar
  The "Insert Function" window appears (see Figure 2.3.1)

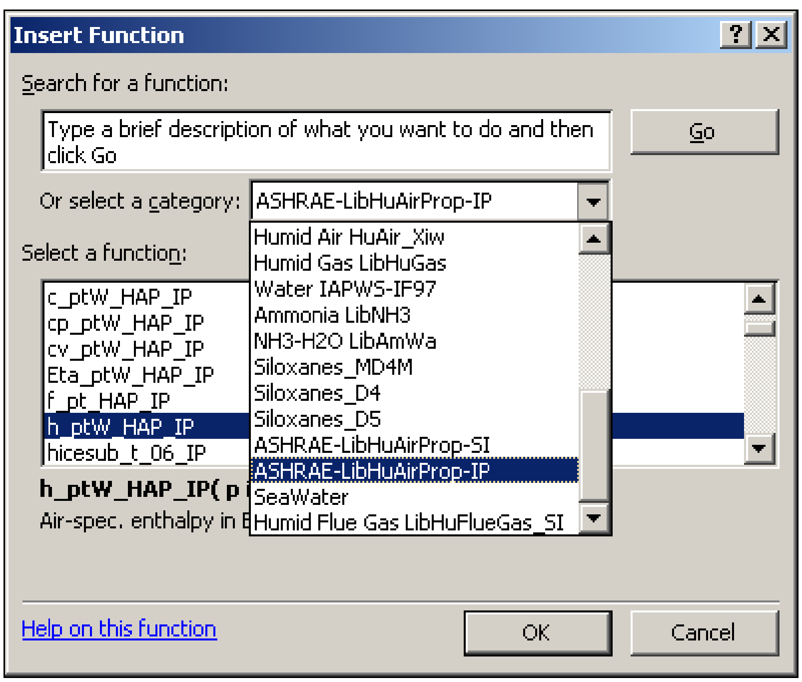

Figure 2.3.1: Choosing the library and function name

- Click on the "ASHRAE-LibHuAirProp-IP" library under "Or select a category:" in the upper part of the window
- Choose the function "h_ptW_HAP_IP" under "Select a function:" directly below that
- Click the "OK" button
  The "Function Arguments" menu for the function "h_ptW_HAP_IP" in the next figure will now appear.

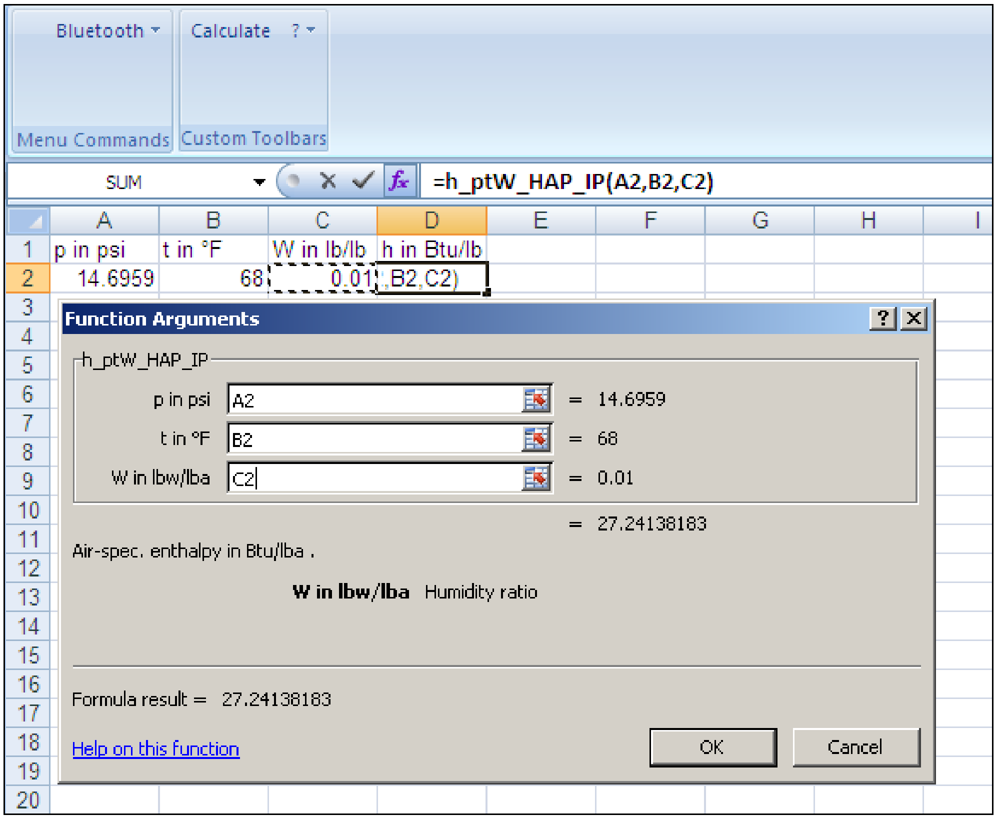

Figure 2.3.2: Input menu for the function

- The cursor is now situated on the line next to "p in psi." You can now enter the value for the mixture pressure *p* either by clicking the cell with the value for *p*, by entering the name of the cell, or by entering the value for *p* directly into the line next to "p in psi."

  ⇒ e. g.: Click on cell A2

- Situate the cursor on the line next to "*t* in °F" and enter the value for *t* either by clicking the cell with the value for *t*, by entering the name of the cell, or by entering the value for *t* directly into the line next to "*t* in °F."

  ⇒ e. g.: Type B2 into the line next to "t in °F"

- Situate the cursor on the line next to "*W* in lb_w/lb_a" and enter the value for the humidity ratio *W* either by clicking the cell with the value for *W*, by entering the name of the cell, or by entering the value for *W* directly into the line next to "*W* in lb_w/lb_a.

  ⇒ e. g.: Click on cell C2

  - It is possible to get detailed information on the "h_ptW_HAP_IP" property function.

- Click the blue "Help on this function" link in the lower left-hand edge of the "Function Arguments" window.

You may be informed that the "LibHuAirProp_IP.hlp" function help cannot be found. In this case, confirm the question whether you want to look for it yourself with "Yes." Select the "LibHuAirProp_IP.hlp" file in the installation menu of FluidEXL*Graphics* in the window which is opened, the standard being

C:\Program Files\FluidEXL_Graphics_Eng

and click "Yes" in order to complete the search.

- Now you should see the help page of the "h_ptW_HAP_IP" property function (see Figure 2.3.3).

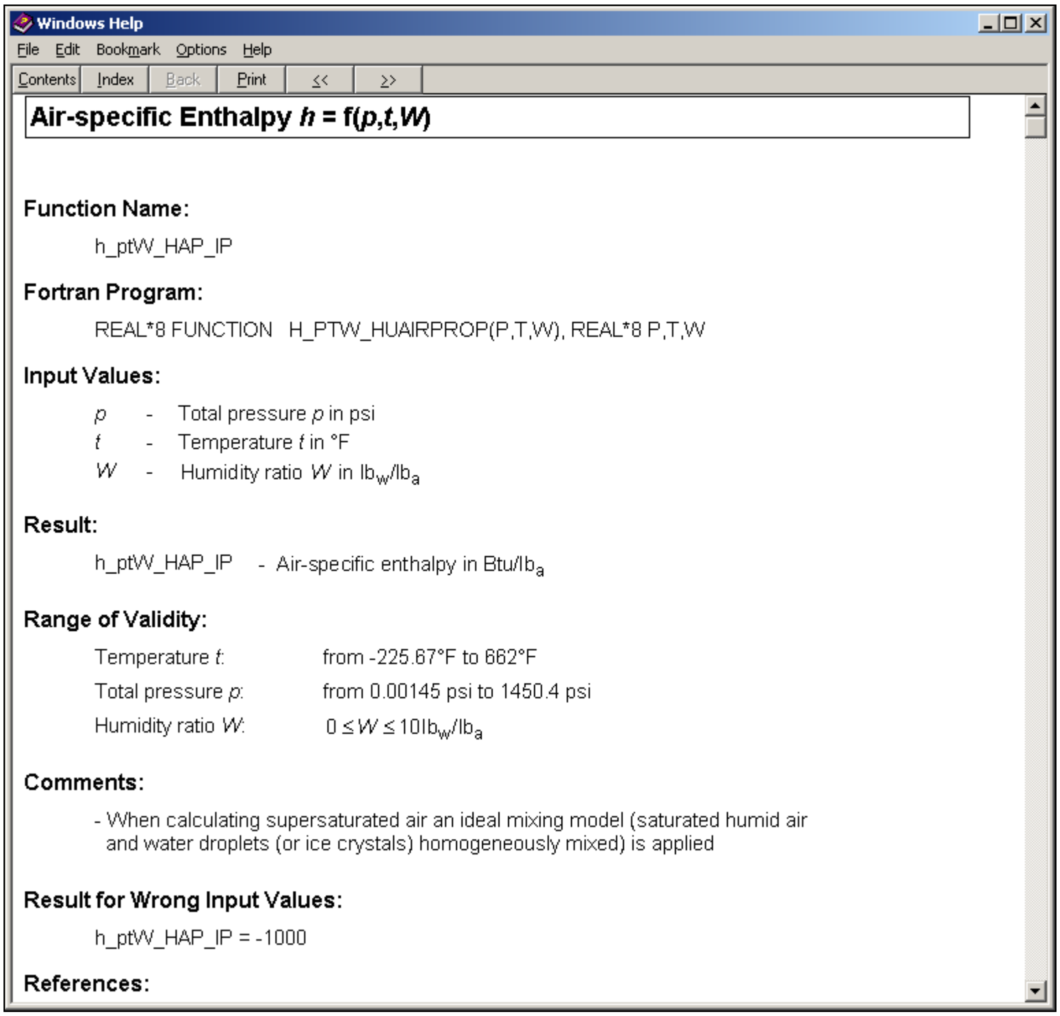

Figure 2.3.3: Help page for the "h_ptW_HAP_IP" function

- Click the "OK" button

The result for h in Btu/lb$_a$ appears in the cell selected above.

⇒ The cell D2 now contains the value 27.24138183.

The calculation of $h = f(p,t,W)$ has thus been completed.

You can now arbitrarily change the values for p, t or W in the appropriate cells. The specific enthalpy h is recalculated and updated every time you change the data. This shows that the Excel® data flow and the DLL calculations are working together successfully

Note:

If the calculation result is -1000, this indicates that the values entered are located outside the range of validity of real moist air. More detailed information on each function and its range of validity is available in Chapter 3.

For further property functions calculable in FluidEXL*Graphics* see the function table in Chapter 1.

2.4 Removing FluidEXL*Graphics* including LibHuAirProp

Should you wish to remove only the LibHuAirProp-IP library, delete the files

LibHuAirProp_IP.dll and LibHuAirProp_IP.hlp

in the directory selected for the installation of FluidEXL*Graphics* (the standard being

C:\Program Files\FluidEXL_Graphics_Eng)

by using an appropriate program such as Windows Explorer®, or Norton Commander®.

Should you wish to remove only the LibHuAirProp-SI library, delete the files

LibHuAirProp_SI.dll and LibHuAirProp_SI.hlp

in the directory selected for the installation of FluidEXL*Graphics* (the standard being

C:\Program Files\FluidEXL_Graphics_Eng)

by using an appropriate program such as Windows Explorer®, or Norton Commander®.

Unregistering FluidEXL*Graphics* as Add-In in Excel® versions 2003 or earlier

To remove FluidEXL*Graphics* and both LibHuAirProp_IP and LibHuAirProp_SI completely, proceed as follows: First cancel the registration of "FluidEXL_Graphics_Eng.xla" has to be deleted in Excel®.

In order to do that, click "Tools" in the upper menu bar of Excel® and here "Add-Ins…" Unmark the box on the left-hand side of

"FluidEXL Graphics Eng"

in the window that appears and click the "OK" button. The additional FluidEXL*Graphics* menu bar will disappear from the upper menu of the Excel® window. Afterwards, we recommend closing Excel®.

As the next step, delete the files

LibHuAirProp_IP.dll, LibHuAirProp_IP.hlp
LibHuAirProp_SI.dll, LibHuAirProp_SI.hlp

in the directory selected for the installation of FluidEXL*Graphics*, the standard being

C:\Program Files\FluidEXL_Graphics_Eng,

using an appropriate program such as Explorer® or Norton Commander®.

In order to remove FluidEXL*Graphics* from Windows® and the hard drive, click "Start" in the Windows® task bar, select "Settings" and click "Control Panel."

Now double-click on "Add or Remove Programs."

In the list box of the "Add or Remove Programs" window that appears, select "FluidEXL Graphics LibHuAirProp" by clicking on it and click the "Add/Remove…" button.

In the following dialog box click "Automatic" and then "Next >."

Click "Finish" in the "Perform Uninstall" window.

Answer the question whether all shared components shall be removed with "Yes to All." Finally, close the "Add or Remove Programs" and "Control Panel" windows®.

Now FluidEXL*Graphics* has been removed.

Unregistering FluidEXL^{Graphics} as Add-In in Excel® 2007 (or later versions)

In order to unregister the FluidEXL^{Graphics} Add-In in Excel® 2007, start Excel® and carry out the following commands:

- Click the Windows Office® button in the upper left hand corner of Excel®
- Click on the "Excel Options" button in the menu which appears (see Figure 2.4.1)

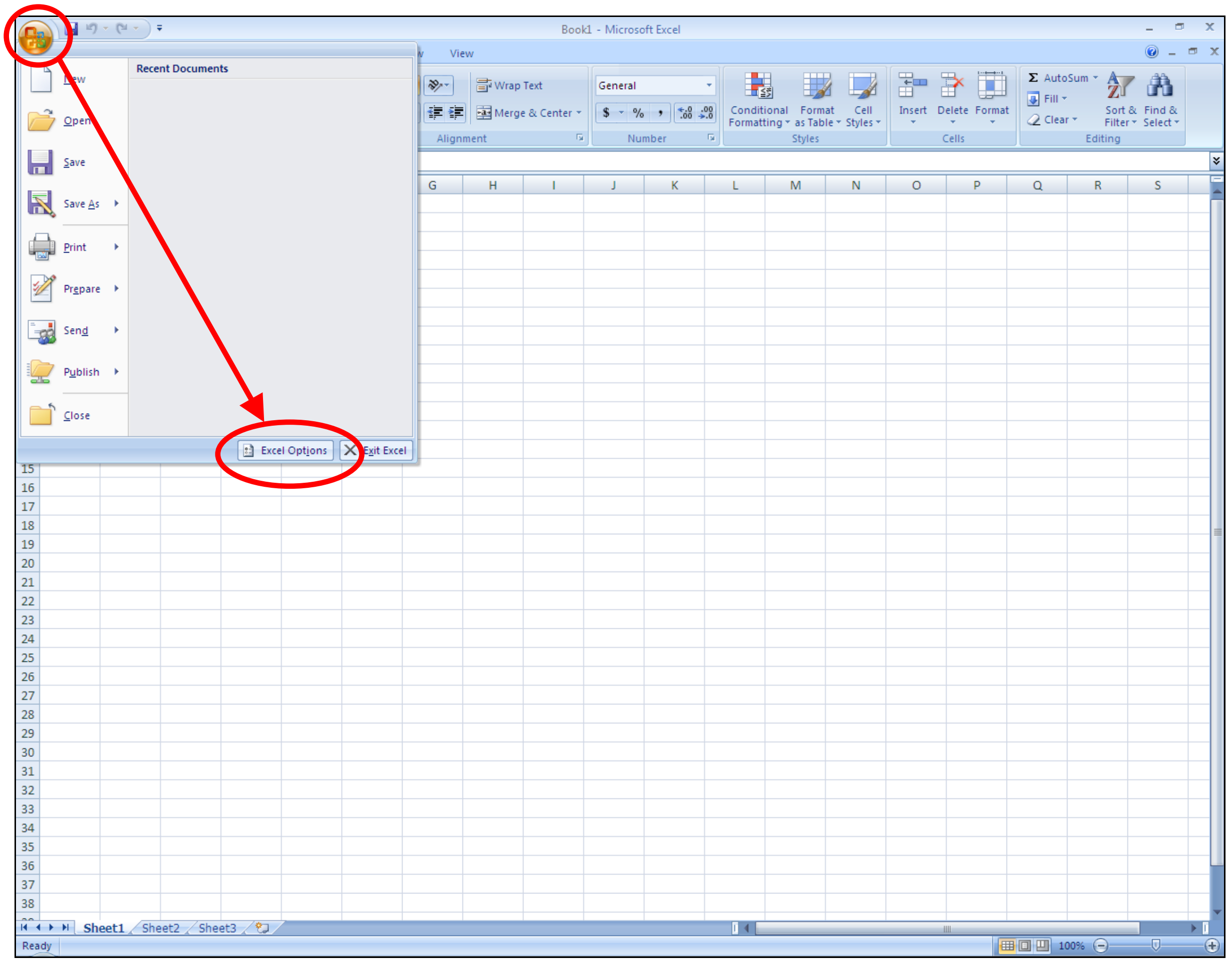

Figure 2.4.1: Unregistering FluidEXL^{Graphics} as Add-In in Excel® 2007

- Click on "Add-Ins" in the next menu (see Figure 2.4.2)

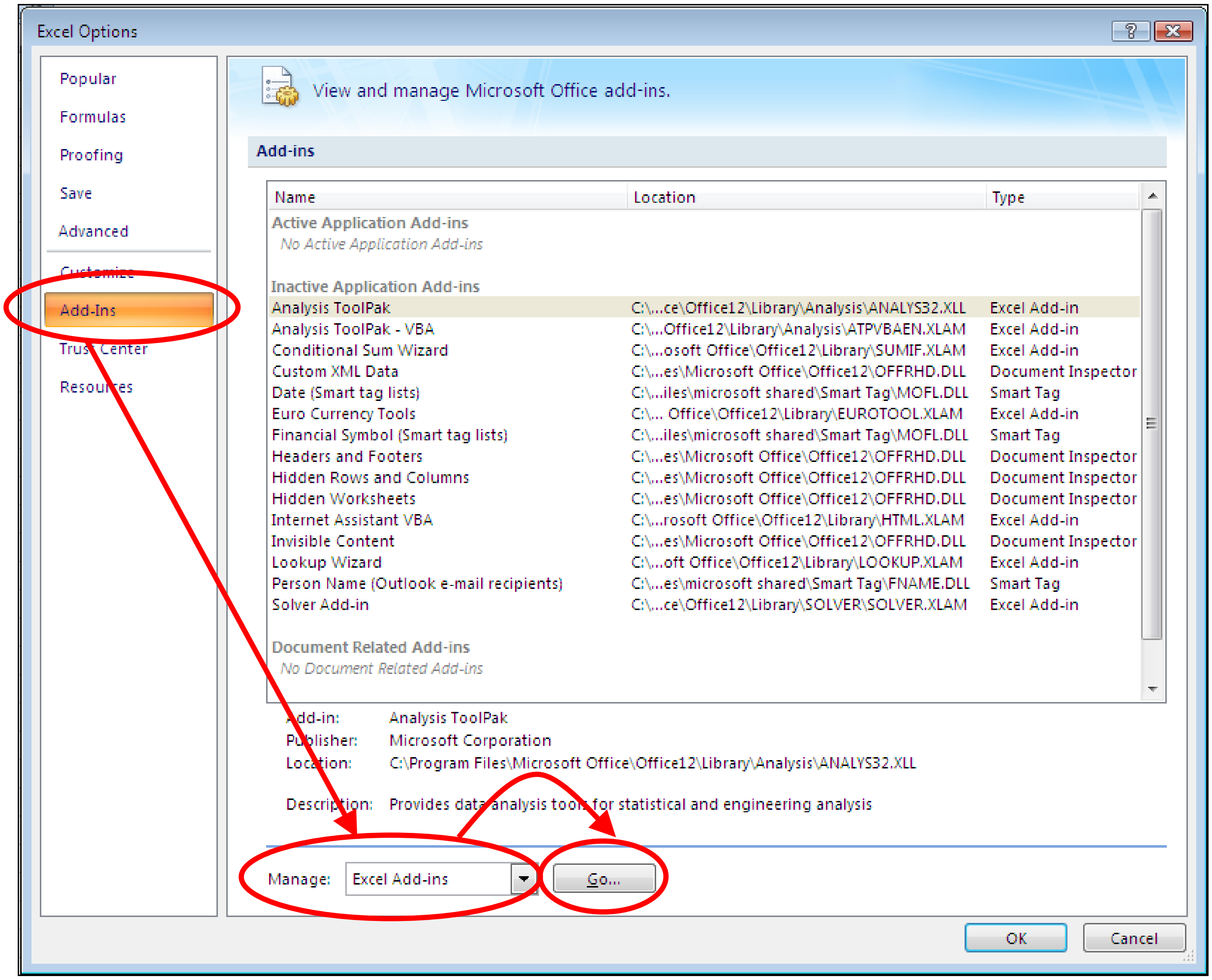

Figure 2.4.2: Dialog window "Add-Ins"

- If it is not shown in the list automatically, chose and select "Excel Add-ins" next to "Manage:" in the lower area of the menu
- Then click the "Go…" button
- Remove the checkmark in front of "FluidEXL Graphics Eng" in the window which now appears. Click the "OK" button to confirm your entry (see Figure 2.4.5).

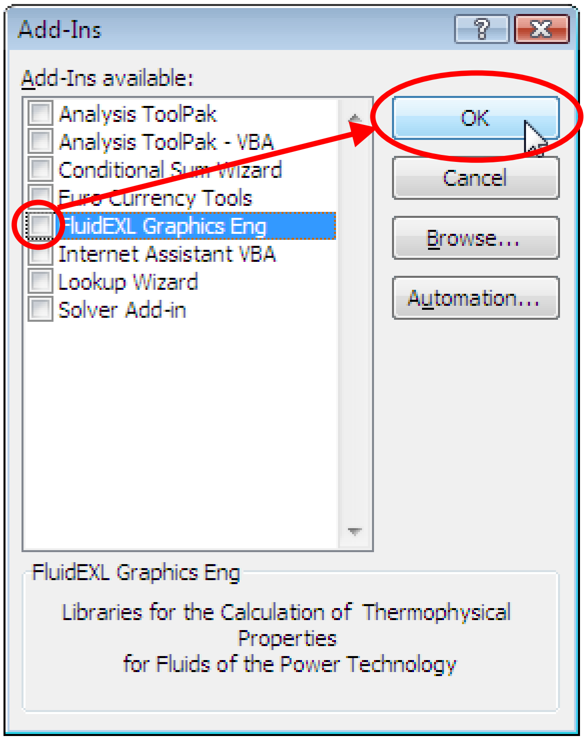

Figure 2.4.5: Dialog window "Add-Ins"

In order to remove FluidEXL*Graphics* from Windows and the hard drive, click "Start" in the Windows task bar, select "Settings" and click "Control Panel."

Now, double click on "Add or Remove Programs."

In the list box of the "Add or Remove Programs" window that appears, select "FluidEXL Graphics Eng" by clicking on it and then clicking the "Add/Remove…" button.

Click "Automatic" in the following dialog box and then the "Next >" button.

Click "Finish" in the "Perform Uninstall" window.

Answer the question of whether all shared components should be removed with "Yes to All."
Finally, close the "Add or Remove Programs" and "Control Panel" windows.

Now FluidEXL*Graphics* has been completely removed from your computer.

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 lb_w/lb_a

Result:

a_ptW_HAP_IP - Thermal diffusivity of humid air 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:

- Thermal diffusivity $a = \frac{\lambda}{\rho \cdot c_p}$
- Calculation for supersaturated humid air ($W > W_s$) 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 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 lb_w/lb_a

Result:

betap_ptW_HAP_IP - Isothermal stress coefficient of humid air in 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: $0 \le W \le W_s$

Comments:

- Isothermal stress coefficient $\beta_p = -\frac{1}{p}\left(\frac{\partial p}{\partial v}\right)_T$

- Calculation for supersaturated humid air ($W > W_s$) 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 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*:	$0 \le W \le 10\, lb_w/lb_a$

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 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:	$0 \le W \le W_s$

Comments:

- 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_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 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:	$0 \le W \le W_s$

Comments:

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

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

  for $t < 32$°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 lb_w/lb_a

Result:

h_ptW_HAP_IP - Air-specific enthalpy in 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*: $0 \leq W \leq 10\, lb_w/lb_a$

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 $\eta = f(p,t,W)$

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

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]

$\eta_w(p,t)$ IAPWS-IF97 [7], [8] and IAPWS-06 [19]

$\eta_a(t)$ 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 $t \ge 32$°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 $\lambda = \mathrm{f}(p,t,W)$

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

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

- $p(z_{ele}) = 14.696\,\text{psi} \cdot \left(1 - 6.8754 \cdot 10^{-6} \cdot \frac{z_{ele}}{\text{ft}}\right)^{5.256}$

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

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 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:	$0 \le W \le 10$ lb_w/lb_a

Comments:

- Relative humidity $\varphi = \dfrac{p_{H2O}}{p_{H2O,s}}$
- This equation is valid for $p_{H2O} \le p_{H2O,s}$ 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 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:	$0 \le W \le 10 lb_w/lb_a$

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_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 $\psi_{\mathrm{Air}} = \mathrm{f}(W)$

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 lb_w/lb_a

Result:

PsiH2O_W_HAP_IP - Mole fraction of water in humid air in mol_w/mol

Range of Validity:

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

Comments:

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

Result for Wrong Input Values:

PsiH2O_W_HAP_IP = -1000

References:

$\psi_{H2O}(W)$ 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 lb_w/lb_a

Result:

Rho_ptW_HAP_IP - Density of humid air in 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:	$0 \le W \le 10\, lb_w/lb_a$

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 lb_w/lb_a

Result:

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

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*: $0 \le W \le 10\, lb_w/lb_a$

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 = f(p,t,W) using W = f(p,t,φ)

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*:	$0 \le W \le 10\, lb_w/lb_a$

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 $\mathrm{Btu/(lb_a \cdot °R)}$

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 $\mathrm{Btu/(lb_a\ °R)}$ to 9.32877 $\mathrm{Btu/(lb_a\ °R)}$
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 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:	$0 \le W \le 10\,lb_w/lb_a$

Comments:

- Iteration of wet-bulb temperature t_{wb} from $h^{unsaturated}(p,t,W) = h^{fog}(p,t_{wb},W)$
- 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 lb_w/lb_a

Result:

u_ptW_HAP_IP - Air-specific internal energy in 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: $0 \le W \le 10\, lb_w/lb_a$

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 lb_w/lb_a

Result:

v_ptW_HAP_IP - Air-specific volume in 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:	$0 \le W \le 10$ 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 lb_w/lb_a

Result:

XiAir_W_HAP_IP - Mass fraction of (dry) air in humid air in lb_a/lb

Range of Validity:

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

Comments:

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

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 = 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 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 $Z = 1 + \frac{B_m}{\bar{v}} + \frac{C_m}{\bar{v}^2}$

  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 ($W > W_s$) 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 $h_{liq} = f(p,t)$

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 $p_s(32°F) = 0.08865$ psi to 1450.4 psi

Temperature *t*: from 32°F to 662°F

Comments:

- Specific enthalpy of liquid water $h_{liq} = h^{97}(p,t)$ (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 $h_{liq,s} = f(t)$

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 $h_{liq,s} = h^{97}(p_s, t)$ (Region 1)
  with $p_s = p_s^{97}(t)$

Result for Wrong Input Values:

hliqs_t_97_IP = -1000

References:

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

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

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 $h_{vap,s} = h^{97}(p_s, t)$ (Region 2)
  with $p_s = p_s^{97}(t)$

Result for Wrong Input Values:

hvaps_t_97_IP = -1000

References:

$h^{97}(p,t)$, $p_s^{97}(t)$ 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 $s_{liq} = f(p,t)$

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 $p_s(32°F) = 0.08865$ psi to 1450.4 psi

Temperature *t*: from 32°F to 662°F

Comments:

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

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 $s_{liq,s} = s^{97}(p_s, t)$ (Region 1)
  with $p_s = p_s^{97}(t)$

Result for Wrong Input Values:

sliqs_t_97_IP = -1000

References:

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

Specific Entropy of Saturated Water Vapor $s_{vap,s}$ = 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 $s_{vap,s} = s^{97}(p_s, t)$ (Region 2)
  with $p_s = p_s^{97}(t)$

Result for Wrong Input Values:

svaps_t_97_IP = -1000

References:

$s^{97}(p,t)$, $p_s^{97}(t)$ 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 $v_{liq} = f(p,t)$

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 ft^3/lb

Range of Validity:

Pressure p:	from $p_s(32°F) = 0.08865$ psi to 1450.4 psi
Temperature t:	from 32°F to 662°F

Comments:

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

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 $v_{vap,s} = f(t)$

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 $v_{vap,s} = v^{97}(p_s, t)$ (Region 2)
  with $p_s = p_s^{97}(t)$

Result for Wrong Input Values:

vvaps_t_97_IP = -1000

References:

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

3.3 Functions for Steam and Water for Temperatures $t \le 32°F$

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

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 $h_{\text{ice,sub}} = h^{06}(p_{\text{sub}}, t)$
  with $p_{\text{sub}} = p_{\text{sub}}^{08}(t)$

Result for Wrong Input Values:

hicesub_t_06_IP = -1000

References:

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

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

Specific Enthalpy of Saturated Water Vapor $h_{vap,sub}$ = 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 $h_{vap,sub} = h^{95}(p_{sub}, t)$

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

Result for Wrong Input Values:

hvapsub_t_95_IP = -1000

References:

$h^{95}(p,t)$ IAPWS-95 [5], [6]

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

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

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:

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

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

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:

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

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

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 $s_{ice,sub} = s^{06}(p_{sub}, t)$
  with $p_{sub} = p_{sub}^{08}(t)$

Result for Wrong Input Values:

sicesub_t_06_IP = -1000

References:

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

$p_{sub}^{08}(t)$ 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 x 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 $v_{\mathrm{ice,sub}} = f(t)$

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 ft^3/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 $v_{vap,sub} = f(t)$

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 $v_{vap,sub} = v^{95}(p_{sub}, t)$
  with $p_{sub} = p_{sub}^{08}(t)$

Result for Wrong Input Values:

vvapsub_t_95_IP = -1000

References:

$v^{95}(p,t)$ IAPWS-95 [7], [8]

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

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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
  - IAPWS-IF97-S03rev
  - IAPWS-IF97-S04
  - IAPWS-IF97-S05
- IAPWS Revised Advisory Note No. 3 on Thermodynamic Derivatives (2008)

Humid Combustion Gas Mixtures

Library LibHuGas

Model: Ideal mixture of the real fluids:

CO_2 - Span and Wagner
H_2O - IAPWS-95
N_2 - Span et al.
O_2 - Schmidt and Wagner
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 and 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 the VDI 4670
- Poynting effect from ASHRAE RP-1485

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

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 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	Ethyl alcohol
CH_3OH	Methyl alcohol
$C_3H_8O_3$	Glycerol
K_2CO_3	Potassium carbonate
$CaCl_2$	Calcium chloride
$MgCl_2$	Magnesium chloride
NaCl	Sodium chloride
$C_2H_3KO_2$	Potassium acetate

Formulation of the International Institute of Refrigeration (1997)

Ethanol
Library LibC2H5OH
Formulation of Schroeder (2012)

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
Library LibN2
Formulation of Span et al. (2000)

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**
Dinitrogen monooxide N_2O **Library LibN2O**
Sulfur dioxide SO_2 **Library LibSO2**
Acetone C_3H_6O **Library LibC3H6O**
Formulation of Lemmon and Span (2006)

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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

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 can be calculated.

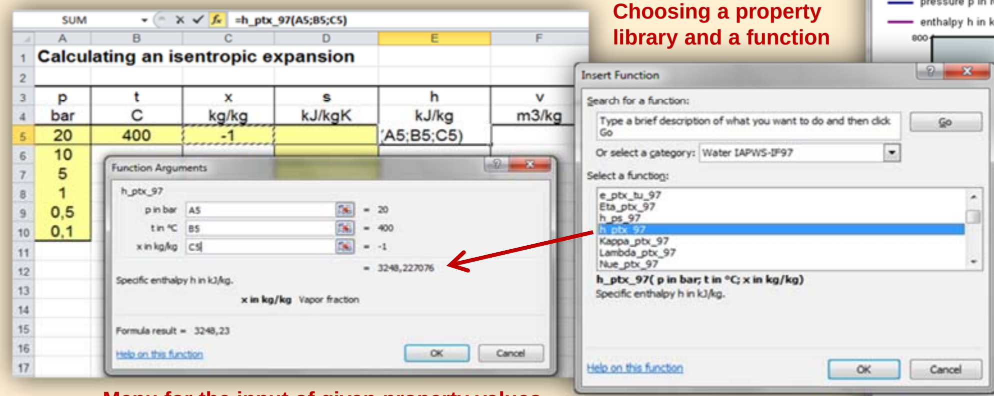
[a] Not all of these property functions are available in all property libraries.

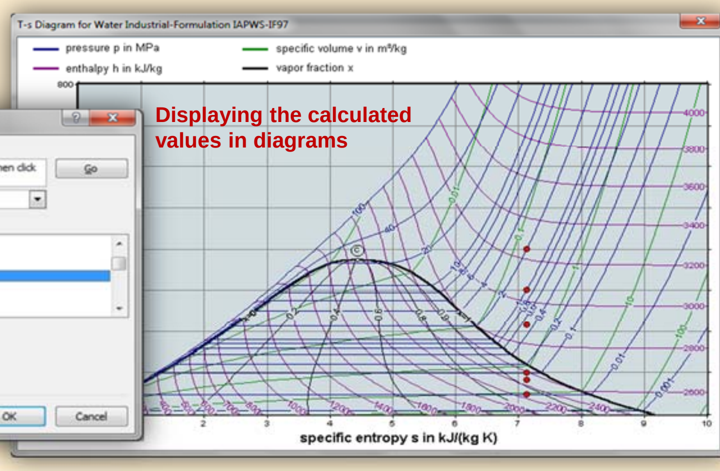
www.thermodynamic-property-libraries.com

ZITTAU/GOERLITZ UNIVERSITY OF APPLIED SCIENCES
Department of Technical Thermodynamics
www.thermodynamics-zittau.de

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

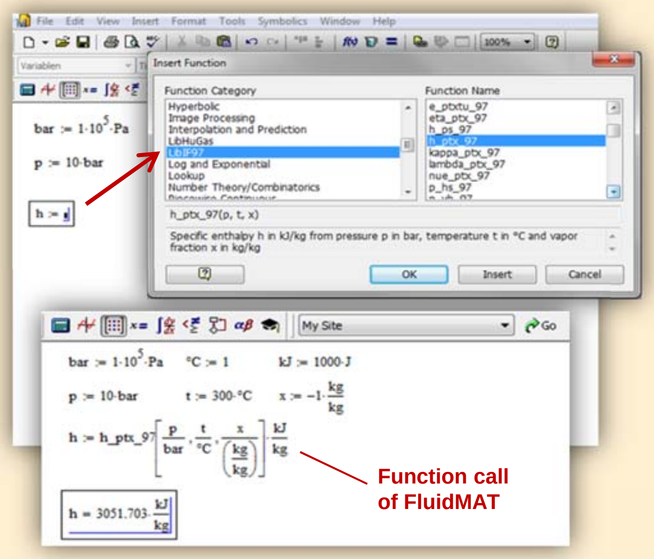
Add-In FluidEXL^{Graphics} for Excel®





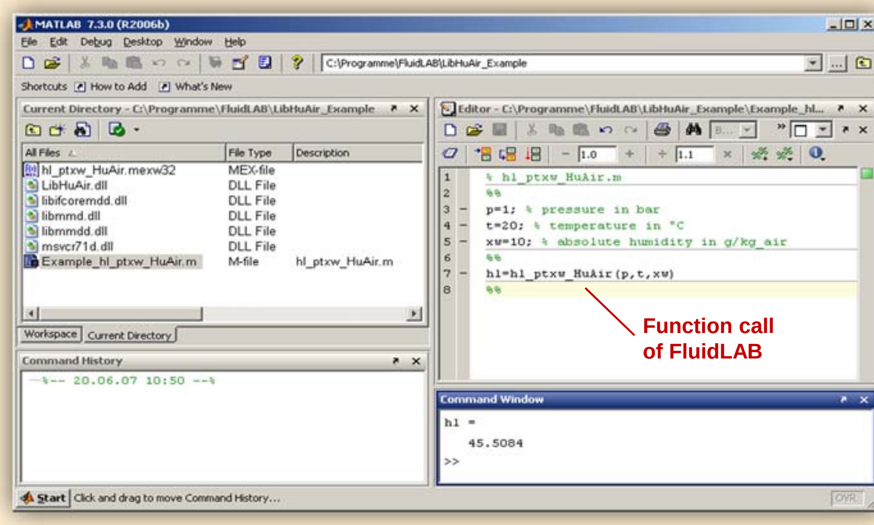
Add-In FluidMAT for Mathcad®

The property libraries can be used in Mathcad®.



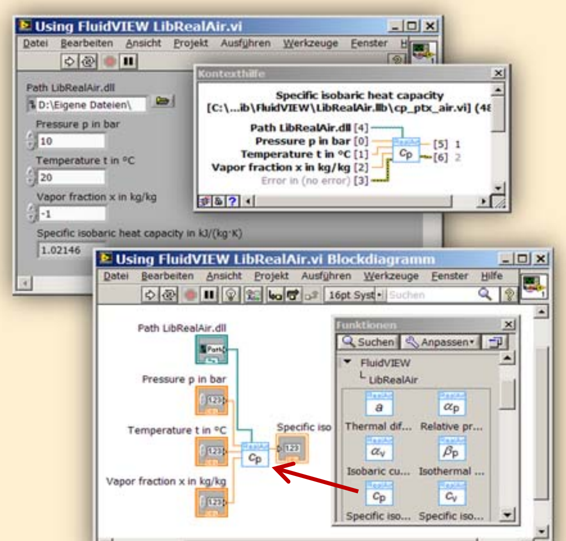
Add-In FluidLAB for MATLAB®

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



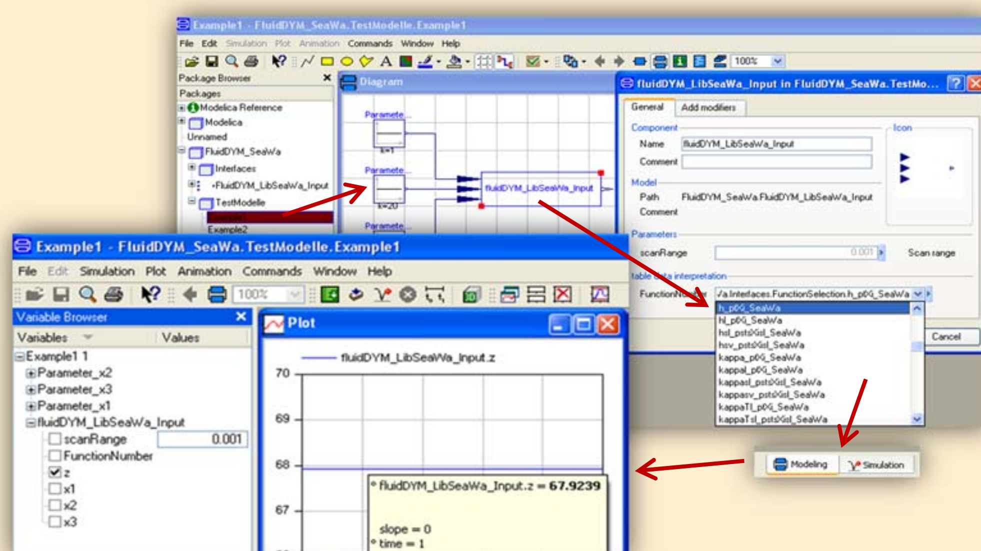
Add-On FluidVIEW for LabVIEW®

The property functions can be calculated in LabVIEW®.

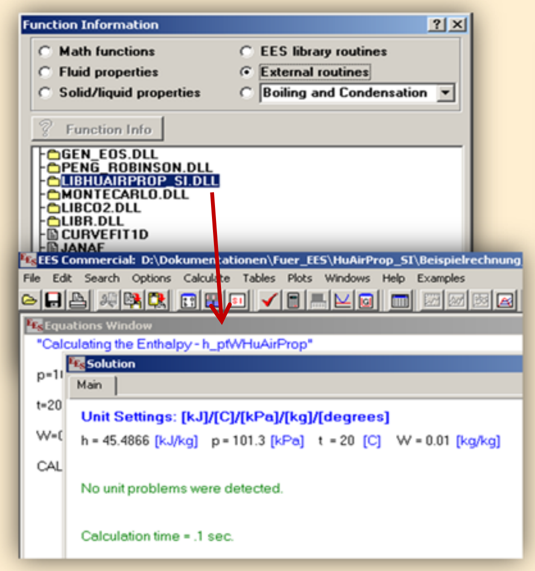


Add-In FluidDYM for DYMOLA® (Modelica) and SimulationX®

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

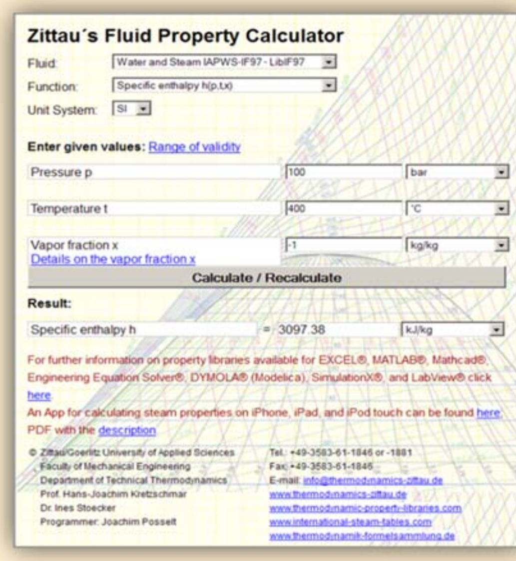


Add-In **FluidEES** for Engineering Equation Solver®



App International Steam Tables for iPhone, iPad, iPod touch, Android smart phones and tablets

Online Property Calculator at www.thermodynamics-zittau.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

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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

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 can be calculated.

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

www.thermodynamic-property-libraries.com

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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
$p = \mathrm{f}(z_{ele})$	p_zele_HAP_SI	Pressure of humid air from elevation	kPa	3/15
$p_{Air} = \mathrm{f}(p,t,W)$	pAIR_ptW_HAP_SI	Partial pressure of dry air in moist air	kPa	3/16
$p_{H2O} = \mathrm{f}(p,t,W)$	pH2O_ptW_HAP_SI	Partial pressure of water vapor in moist air	kPa	3/17
$p_{H2Os} = \mathrm{f}(p,t)$	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
$\varphi = f(p,t,W)$	phi_ptW_HAP_SI	Relative humidity (decimal ratio)	-	3/19
$Pr = f(p,t,W)$	Pr_ptW_HAP_SI	PRANDTL number	-	3/20
$\psi_{Air} = f(W)$	PsiAir_W_HAP_SI	Mole fraction of dry air in moist air	mol_a/mol	3/21
$\psi_{H2O} = f(W)$	PsiH2O_W_HAP_SI	Mole fraction of water vapor in moist air	mol_w/mol	3/22
$\rho = f(p,t,W)$	Rho_ptW_HAP_SI	Density	kg/m^3	3/23
$s = f(p,t,W)$	s_ptW_HAP_SI	Air-specific entropy	$kJ/(kg_a \cdot K)$	3/24
$t = f(p,h,\varphi)$	t_phphi_HAP_SI	Backward function: temperature from total pressure, air-specific enthalpy and relative humidity	°C	3/25
$t = f(p,h,W)$	t_phW_HAP_SI	Backward function: temperature from total pressure, air-specific enthalpy and humidity ratio	°C	3/26
$t = f(p,s,W)$	t_psW_HAP_SI	Backward function: temperature from total pressure, air-specific entropy and humidity ratio	°C	3/27
$t = f(p,t_{wb},W)$	t_ptwbW_HAP_SI	Backward function: temperature from total pressure, wet-bulb temperature and humidity ratio	°C	3/28
$t_d = f(p,W)$	td_pW_HAP_SI	Dew-point/frost-point temperature	°C	3/29
$t_s = f(p,p_{H2O})$	ts_ppH2O_HAP_SI	Backward function: saturation temperature of water from total pressure and partial pressure of water vapor	°C	3/30
$t_{wb} = f(p,t,W)$	twb_ptW_HAP_SI	Wet-bulb/ice-bulb temperature	°C	3/31
$u = f(p,t,W)$	u_ptW_HAP_SI	Air-specific internal energy	kJ/kg_a	3/32
$v = f(p,t,W)$	v_ptW_HAP_SI	Air-specific volume	m^3/kg_a	3/33
$W = f(p,t,p_{H2O})$	W_ptpH2O_HAP_SI	Humidity ratio from total pressure, temperature, and partial pressure of water vapor	kg_w/kg_a	3/34
$W = f(p,t,\varphi)$	W_ptphi_HAP_SI	Humidity ratio from total pressure, temperature, and relative humidity	kg_w/kg_a	3/35
$W = f(p,t_d)$	W_ptd_HAP_SI	Humidity ratio from total pressure and dew-point temperature	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	kg_w/kg_a	3/37
$W_{\mathrm{s}} = \mathrm{f}(p,t)$	Ws_pt_HAP_SI	Saturation humidity ratio	kg_w/kg_a	3/38
$\xi_{\mathrm{Air}} = \mathrm{f}(W)$	XiAir_W_HAP_SI	Mass fraction of dry air in moist air	kg_a/kg	3/39
$\xi_{\mathrm{H2O}} = \mathrm{f}(W)$	XiH2O_W_HAP_SI	Mass fraction of water vapor in moist air	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	≤	p	≤	10 000	kPa
Temperature:	–143.15	≤	t	≤	350	°C
Humidity ratio:	0	≤	W	≤	10	kg_w/kg_a
Relative humidity:	0	≤	φ	≤	1	(decimal ratio)
Dew-point temperature:	–143.15	≤	t_d	≤	350	°C
Wet-bulb temperature:	–143.15	≤	t_{wb}	≤	350	°C

Units

Symbol	Quantity	Unit
p	Pressure	kPa
t	Temperature	°C
W	Humidity ratio	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

Range of Validity of Transport Properties

Property	Range of Validity					
Pressure:	0.01	≤	p	≤	10 000	kPa
Temperature:	–73.15	≤	t	≤	350	°C
Humidity ratio:	0	≤	W	≤	10	kg_w/kg_a
Relative humidity:	0	≤	φ	≤	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°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)

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_9_SI	Specific volume of liquid water	m³/kg	3/51
$v_{liq,s} = f(t)$	vliqs_t_97_SI	Specific volume of saturated liquid water	m³/kg	3/52
$v_{vap,s} = f(t)$	vvaps_t_97_SI	Specific volume of saturated water vapor	m³/kg	3/53

Range of Validity

Property	Range of Validity
Pressure:	0.01 ≤ p ≤ 10 000 kPa
Temperature:	0 ≤ t ≤ 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 $t \le 0°C$

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	m^3/kg	3/63
$v_{vap,sub} = f(t)$	vvapsub_t_95_SI	Specific volume of saturated water vapor	m^3/kg	3/64

Range of Validity

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

Units

Symbol	Quantity	Unit
p	Pressure	kPa
t	Temperature	°C

Reference State

Property	Water Vapor and Ice
Pressure	$p_s(0.01°C) = 0.611657$ 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	$\frac{a_{IP}}{\frac{ft^2}{s}} = \frac{a_{SI}}{\frac{m^2}{s}} \times 10.76391042$	$\frac{a_{SI}}{\frac{m^2}{s}} = \frac{a_{IP}}{\frac{ft^2}{s}} \times 0.0929304$	m²/s	ft²/s
Relative pressure coefficient	α_p	$\frac{\alpha_{p,IP}}{\frac{1}{°R}} = \frac{\alpha_{p,SI}}{\frac{1}{K}} \times \frac{9}{5}$	$\frac{\alpha_{p,SI}}{\frac{1}{K}} = \frac{\alpha_{p,IP}}{\frac{1}{°R}} \times \frac{5}{9}$	1/K	1/°R
Isothermal stress coefficient	β_p	$\frac{\beta_{p,IP}}{\frac{lb}{ft^3}} = \frac{\beta_{p,SI}}{\frac{kg}{m^3}} \times 0.062428$	$\frac{\beta_{p,SI}}{\frac{kg}{m^3}} = \frac{\beta_{p,IP}}{\frac{lb}{ft^3}} \times 16.018463$	kg/m³	lb/ft³
Speed of sound	c	$\frac{c_{IP}}{\frac{ft}{s}} = \frac{c_{SI}}{\frac{m}{s}} \times 3.2808399$	$\frac{c_{SI}}{\frac{m}{s}} = \frac{c_{IP}}{\frac{ft}{s}} \times 0.3048$	m/s	ft/s
Specific isobaric heat capacity	c_p	$\frac{c_{p,IP}}{\frac{Btu}{lb\ °R}} = \frac{c_{p,SI}}{\frac{kJ}{kg\ K}} \times 0.2388459$	$\frac{c_{p,SI}}{\frac{kJ}{kg\ K}} = \frac{c_{p,IP}}{\frac{Btu}{lb\ °R}} \times 4.1868$	kJ/(kg·K)	Btu/(lb·°R)
Specific isochoric heat capacity	c_v	$\frac{c_{v,IP}}{\frac{Btu}{lb\ °R}} = \frac{c_{v,SI}}{\frac{kJ}{kg\ K}} \times 0.2388459$	$\frac{c_{v,SI}}{\frac{kJ}{kg\ K}} = \frac{c_{v,IP}}{\frac{Btu}{lb\ °R}} \times 4.1868$	kJ/(kg·K)	Btu/(lb·°R)
Dynamic viscosity	η	$\frac{\eta_{IP}}{\frac{lb\ s}{ft^2}} = \frac{\eta_{SI}}{\frac{Pa}{s}} \times 0.02088543$	$\frac{\eta_{SI}}{\frac{Pa}{s}} = \frac{\eta_{IP}}{\frac{lb\ s}{ft^2}} \times 47.880259$	Pa·s	lb·s/ft²
Enhancement factor	f	$f_{IP} = f_{SI}$	$f_{SI} = f_{IP}$	-	-

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	$\frac{\nu_{IP}}{\frac{ft^2}{s}} = \frac{\nu_{SI}}{\frac{m^2}{s}} \times 10.763910417$	$\frac{\nu_{SI}}{\frac{m^2}{s}} = \frac{\nu_{IP}}{\frac{ft^2}{s}} \times 0.092903040$	m²/s	ft²/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/m³	lb/ft³
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$_a$·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	$\frac{s_{IP}}{\frac{Btu}{lb_a\ °R}} = \frac{s_{SI}}{\frac{kJ}{kg_a\ K}} \times 0.23884589$	$\frac{s_{SI}}{\frac{kJ}{kg_a\ K}} = \frac{s_{IP}}{\frac{Btu}{lb_a\ °R}} \times 4.1868$	kJ/(kg$_a$·K)	Btu/(lb$_a$·°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
Air-specific volume (moist air)	v	$\frac{v_{IP}}{\frac{ft^3}{lb_a}} = \frac{v_{SI}}{\frac{m^3}{kg_a}} \times 16.018453$	$\frac{v_{SI}}{\frac{m^3}{kg_a}} = \frac{v_{IP}}{\frac{ft^3}{lb_a}} \times 0.062428$	m³/kg$_a$	ft³/lb$_a$
Specific volume (water, water vapor, ice)	v_w	$\frac{v_{IP}}{\frac{ft^3}{lb}} = \frac{v_{SI}}{\frac{m^3}{kg}} \times 16.018453$	$\frac{v_{SI}}{\frac{m^3}{kg}} = \frac{v_{IP}}{\frac{ft^3}{lb}} \times 0.062428$	m³/kg	ft³/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 $t \geq 0°C$ and from IAPWS-95 [5], [6] for $t \leq 0°C$
- 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]
- the calculation of the second and third molar virial coefficients B_{ww} and C_{www} for water and steam from IAPWS-95 [5], [6]
- 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 $t \geq 0°C$ and of the sublimation pressure of water from IAPWS-08 [11] for $t \leq 0°C$
- the calculation of the isothermal compressibility of saturated liquid water from IAPWS-IF97 [7], [8], [9] for $t \geq 0°C$ and that of ice from IAPWS-06 [10] for $t \leq 0°C$ 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.

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 $p_{subl}^{08}(t)$ [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.

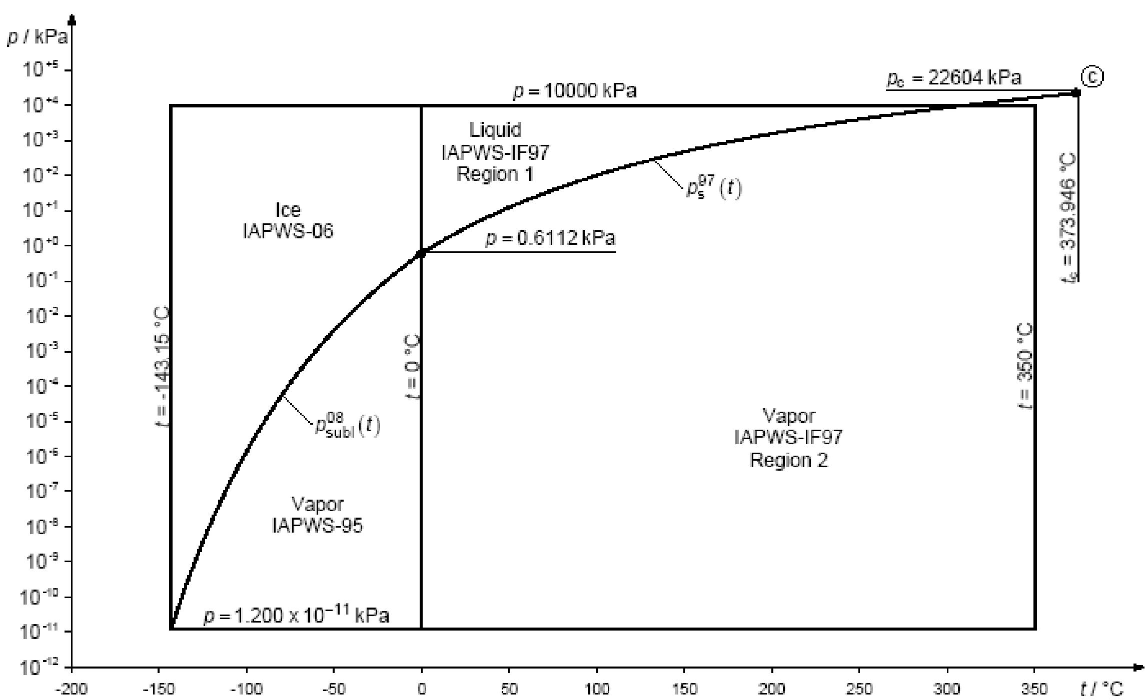


Figure 1: *p-T* diagram with used IAPWS formulations for steam, water, and ice.

2 Add-In FluidEXL*Graphics* for Excel® for ASHRAE-LibHuAirProp-SI

2.1 Installing FluidEXL*Graphics*

The FluidEXL*Graphics* Add-In has been developed to calculate thermophysical properties in Excel® more conveniently. Within Excel®, it enables the direct call of functions relating to real moist air, steam, water, and ice from the ASHRAE-LibHuAirProp-SI property library.

2.1.1 Installing FluidEXL*Graphics* including LibHuAirProp

The installation of FluidEXL*Graphics* 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*)

We will now calculate, step by step, the air-specific enthalpy *h* of real moist air as a function of total pressure *p*, temperature *t* and humidity ratio *W*, using FluidEXL*Graphics*. The following description relates to Excel® 2003. The procedure is analogous for Excel® 97, 2000, XP, and 2007.

Please carry out the following steps:

- Start Excel®
- Enter the value for *p* in kPa into a cell
  (Range of validity: p = 0.01 … 10 000 kPa

  ⇒ e.g.: Enter the value 101.325 into cell A2
- Enter the value for *t* in °C into a cell
  (Range of validity: t = –143.15 ... 350°C)

  ⇒ e.g.: Enter the value 20 into cell B2
- Enter the value for *W* in kg_w/kg_a (*kg water* per *kg air*) into a cell
  (Range of validity: W = 0 … 10 kg_w/kg_a)

  ⇒ e.g.: Enter the value 0.01 into cell C2
- Click the cell in which the air-specific enthalpy *h* in kJ/kg_a is to be displayed
  ⇒ e.g.: Click the cell D2
- Click "Calculate" in the FluidEXL*Graphics* menu bar
  The "Insert Function" window appears (see Figure 2.1.1.)

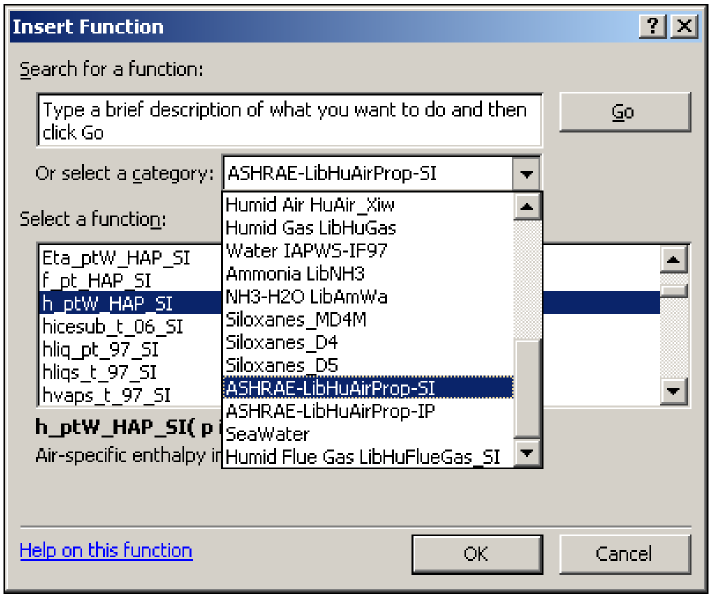


Figure 2.1.1: Choosing the library and function name

- Search and click the "ASHRAE-LibHuAirProp-SI" library under "Or select a category:" in the upper part of the window
- Search and click the "h_ptW_HAP_SI" function under "Select a function:" right below
- Click the "OK" button
  The "Function Arguments" menu for the function "h_ptW_HAP_SI" in the next figure will now appear.

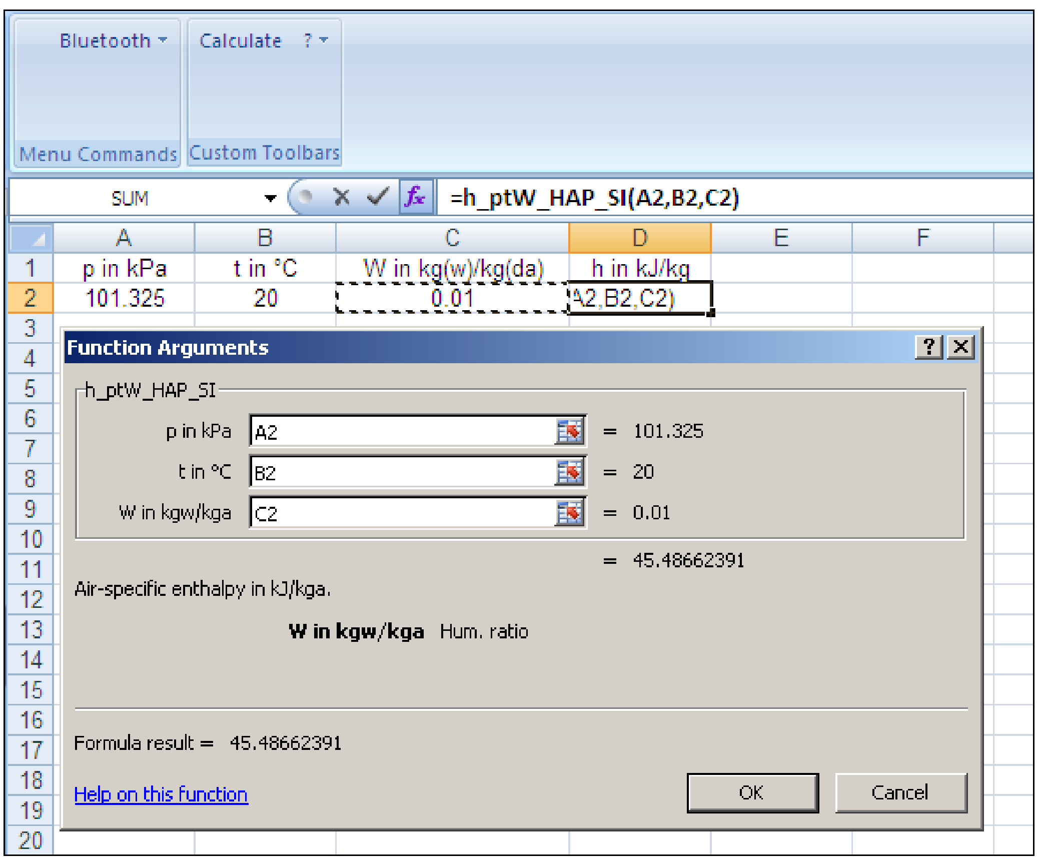


Figure 2.1.2: Input menu for the function

- The cursor is now situated on the line next to "p in kPa". You can now enter the value for the mixture pressure p either by clicking the cell with the value for p, by entering the name of the cell, or by entering the value for p directly into the line next to "p in kPa".

  ⇒ e. g.: Click the cell A2

- Situate the cursor on the line next to "t in °C" and enter the value for t either by clicking the cell with the value for t, by entering the name of the cell, or by entering the value for t directly into the line next to "t in °C".

  ⇒ e. g.: Type B2 into the line next to "t in °C"

- Situate the cursor on the line next to "W in kg_w/kg_a" and enter the value for the humidity ratio W either by clicking the cell with the value for W, by entering the name of the cell, or by entering the value for W directly into the line next to "W in kg_w/kg_a.

  ⇒ e. g.: Click the cell C2

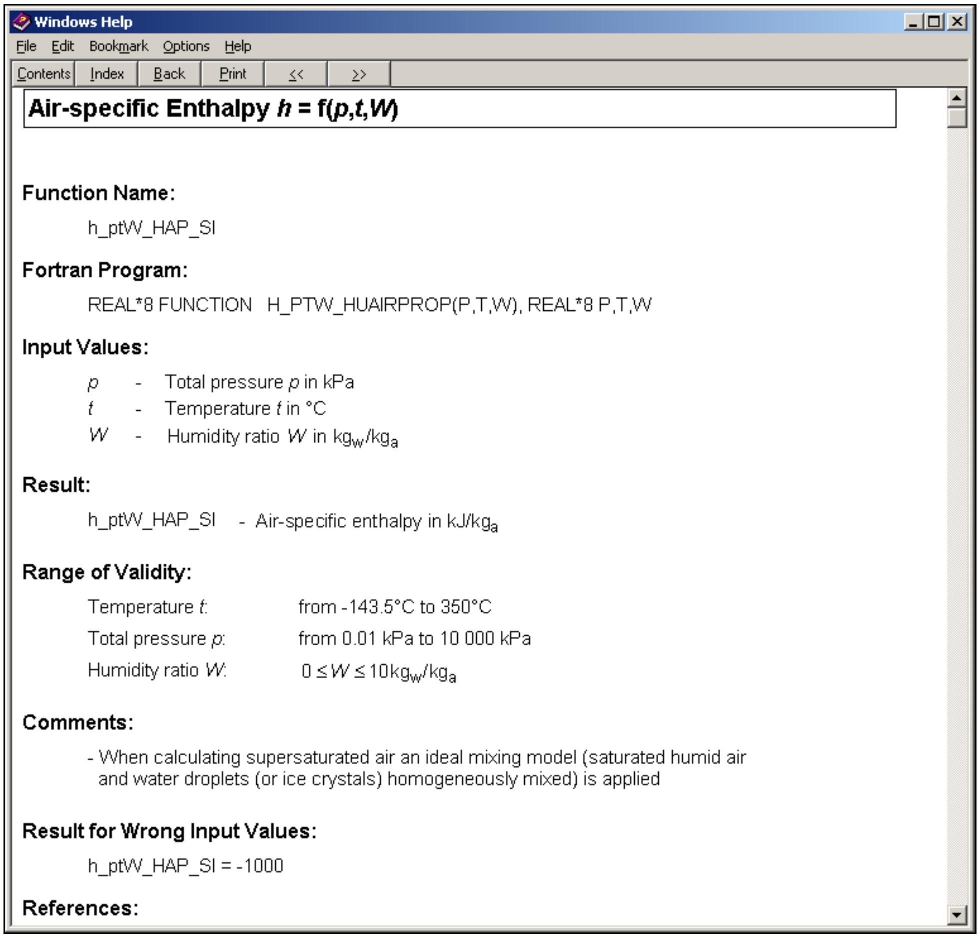
- Here it is possible to get detailed information on the "h_ptW_HAP_SI" property function.
- Click the blue "Help on this function" link in the lower left-hand edge of the "Function Arguments" window.

You may be informed that the "LibHuAirProp_SI.hlp" function help cannot be found. In this case, confirm the question whether you want to look for it yourself with "Yes". Search and click on the "LibHuAirProp_SI.hlp" file in the installation menu of FluidEXL*Graphics* in the window which is opened, in the standard case

C:\Program Files\FluidEXL_Graphics_Eng

and click "Yes" in order to complete the search.

- Now you should see the help page of the "h_ptW_HAP_SI" property function (see Figure 2.1.3).



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:

Figure 2.1.3: Help page for the "h_ptW_HAP_SI" function

- Click the "OK" button

The result for h in kJ/kg_a appears in the cell selected above.

⇒ The cell D2 now contains the value 45.48662391.

The calculation of h = f(p,t,W) has thus been completed.

You can now arbitrarily change the values for p, t or W in the appropriate cells. The specific enthalpy h is recalculated and updated every time you change the data. This shows that the Excel® data flow and the DLL calculations are working together successfully

Note:

If the calculation results in -1000, this indicates that the values entered are located outside the range of validity of real moist air. More detailed information on each function and its range of validity is available in Chapter 3.

For further property functions calculable in FluidEXL*Graphics* see the function table in Chapter 1.

2.3 Removing FluidEXL*Graphics* including LibHuAirProp

The de-installation of FluidEXL*Graphics* 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 kg_w/kg_a

Result:

a_ptW_HAP_SI - Thermal diffusivity of humid air in 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*: $0 \leq W \leq W_s$

Comments:

- Thermal diffusivity $a = \dfrac{\lambda}{\rho \cdot c_p}$
- Calculation for supersaturated humid air ($W > W_s$) 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 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:	$0 \le W \le W_s$

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_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 kg_w/kg_a

Result:

betap_ptW_HAP_SI - Isothermal stress coefficient of humid air in 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:	$0 \le W \le W_s$

Comments:

- Isothermal stress coefficient $\beta_p = -\frac{1}{p}\left(\frac{\partial p}{\partial v}\right)_T$

- Calculation for supersaturated humid air ($W > W_s$) 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 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*:	$0 \le W \le 10\,kg_w/kg_a$

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

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

  for $t < 0.01°\mathrm{C}$ - 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 $\eta = f(p,t,W)$

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 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:	$0 \le W \le 10\,kg_w/kg_a$

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

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 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*:	$0 \le W \le 10\,kg_w/kg_a$

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 $t \ge 0.01$°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 $\lambda = f(p,t,W)$

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 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:	$0 \le W \le 10\, kg_w/kg_a$

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]
$\lambda_a(t)$	Lemmon et al. [18]
$\lambda_w(p,t)$	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 kg_w/kg_a

Result:

Ny_ptW_HAP_SI - Kinematic viscosity in 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:	$0 \leq W \leq W_s$

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*:	$0 \le W \le 10\, kg_w/kg_a$

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 $p = \mathrm{f}(z_{\mathrm{ele}})$

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
- $p(z_{\mathrm{ele}}) = 101.325\,\mathrm{kPa} \cdot \left(1 - 2.25577 \cdot 10^{-5} \cdot \frac{z_{\mathrm{ele}}}{\mathrm{m}}\right)^{5.256}$

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 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: $0 \le W \le 10\,kg_w/kg_a$

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 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:	$0 \le W \le 10\,kg_w/kg_a$

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 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:	$0 \le W \le 10\,kg_w/kg_a$

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_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 $\psi_{\mathrm{Air}} = f(W)$

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 kg_w/kg_a

Result:

PsiAir_W_HAP_SI - Mole fraction of (dry) air in humid air in mol_a/mol

Range of Validity:

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

Comments:

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

Result for Wrong Input Values:

PsiAir_W_HAP_SI = -1000

References:

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

Mole Fraction of Water ψ_{H2O} = 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 kg_w/kg_a

Result:

PsiH2O_W_HAP_SI - Mole fraction of water in humid air in mol_w/mol

Range of Validity:

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

Comments:

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

Result for Wrong Input Values:

PsiH2O_W_HAP_SI = -1000

References:

$\psi_{H2O}(W)$ 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 kg_w/kg_a

Result:

Rho_ptW_HAP_SI - Density of humid air in 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: $0 \le W \le 10\,kg_w/kg_a$

Comments:

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

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 kg_w/kg_a

Result:

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

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:	$0 \le W \le 10\,kg_w/kg_a$

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 $t = f(p,h,\varphi)$

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 $W = f(p,t,\varphi)$

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*:	$0 \le W \le 10\, kg_w/kg_a$

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 $t = \mathrm{f}(p, t_{wb}, W)$

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 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:	$0 \le W \le 10\,kg_w/kg_a$

Comments:

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

Result for Wrong Input Values:

t_ptwbW_HAP_SI = -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_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:	$0 \le W \le 10\,kg_w/kg_a$

Comments:

- Iteration of wet-bulb/ice-bulb temperature t_{wb} from $h^{unsaturated}(p,t,W) = h^{fog}(p,t_{wb},W)$
- 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 kg_w/kg_a

Result:

u_ptW_HAP_SI - Air-specific internal energy in 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*:	$0 \le W \le 10\,kg_w/kg_a$

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:	$0 \leq \varphi \leq 1$

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 $W_s = \frac{M_{H2O}}{M_a} \frac{p_{H2O,s}}{(p - p_{H2O,s})}$

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 kg_w/kg_a

Result:

XiAir_W_HAP_SI - Mass fraction of (dry) air in humid air in kg_a/kg

Range of Validity:

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

Comments:

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

Result for Wrong Input Values:

XiAir_W_HAP_SI = -1000

References:

$\xi_{Air}(W)$ 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: $0 \leq W \leq 10\,kg_w/kg_a$

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 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:	$0 \le W \le W_s$

Comments:

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

  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 ($W > W_s$) is not possible

Result for Wrong Input Values:

Z_ptW_HAP_SI = -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 $t \geq 0°C$

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

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 $p_s(0°C) = 0.6112$ kPa to 10000 kPa

Temperature *t*: from 0°C to 350°C

Comments:

- Specific enthalpy of liquid water $h_{liq} = h^{97}(p,t)$ (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 $h_{liq,s} = f(t)$

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 $h_{liq,s} = h^{97}(p_s, t)$ (Region 1)
  with $p_s = p_s^{97}(t)$

Result for Wrong Input Values:

hliqs_t_97_SI = -1000

References:

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

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

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 $h_{vap,s} = h^{97}(p_s, t)$ (Region 2)
  with $p_s = p_s^{97}(t)$

Result for Wrong Input Values:

hvaps_t_97_SI = -1000

References:

$h^{97}(p,t)$, $p_s^{97}(t)$ 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 $s_{liq} = f(p,t)$

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 $p_s(0°C) = 0.6112$ kPa to 10 000 kPa

Temperature t: from 0°C to 350°C

Comments:

- Specific entropy of liquid water $s_{liq} = s^{97}(p,t)$ (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 $s_{vap,s} = f(t)$

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 $s_{vap,s} = s^{97}(p_s, t)$ (Region 2)
  with $p_s = p_s^{97}(t)$

Result for Wrong Input Values:

svaps_t_97_SI = -1000

References:

$s^{97}(p,t)$, $p_s^{97}(t)$ 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 $v_{liq,s} = f(t)$

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 $v_{liq,s} = v^{97}(p_s, t)$ (Region 1)
  with $p_s = p_s^{97}(t)$

Result for Wrong Input Values:

vliqs_t_97_SI = -1000

References:

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

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

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 $v_{vap,s} = v^{97}(p_s, t)$ (Region 2) with $p_s = p_s^{97}(t)$

Result for Wrong Input Values:

vvaps_t_97_SI = -1000

References:

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

3.3 Functions for Steam and Water 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 $p_{\mathrm{sub}} = p_{\mathrm{sub}}^{08}(t)$

Result for Wrong Input Values:

hvapsub_t_95_SI = -1000

References:

$h^{95}(p,t)$ IAPWS-95 [5], [6]

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

Melting Pressure p_{mel} = 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:

$p_{mel}^{08}(t)$ 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 $s_{ice,sub} = f(t)$

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 $s_{ice,sub} = s^{06}(p_{sub}, t)$
  with $p_{sub} = p_{sub}^{08}(t)$

Result for Wrong Input Values:

sicesub_t_06_SI = -1000

References:

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

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

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

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 $s_{vap,sub} = s^{95}(p_{sub}, t)$
  with $p_{sub} = p_{sub}^{08}(t)$

Result for Wrong Input Values:

svapsub_t_95_SI = -1000

References:

$s^{95}(p,t)$ IAPWS-95 [7], [8]

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

Melting Temperature t_{mel} = 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 $p_s(0°C) = 0.6112$ kPa to 10 000 kPa

Result for Wrong Input Values:

tmel_p_08_SI = -1000

References:

$t_{mel}^{08}(p)$ 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_{subl}(-143.15°C) = 1.2002 x 10^{-11} kPa to p_{subl}(0°C) = 0.6112 kPa

Result for Wrong Input Values:

tsub_p_08_SI = -1000

References:

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

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

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 $v_{\mathrm{ice,sub}} = v^{06}(p_{\mathrm{sub}}, t)$
  with $p_{\mathrm{sub}} = p_{\mathrm{sub}}^{08}(t)$

Result for Wrong Input Values:

vicesub_t_06_SI = -1000

References:

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

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

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www.thermodynamics-zittau.de

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
  - IAPWS-IF97-S03rev
  - IAPWS-IF97-S04
  - IAPWS-IF97-S05
- IAPWS Revised Advisory Note No. 3 on Thermodynamic Derivatives (2008)

Humid Combustion Gas Mixtures

Library LibHuGas

Model: Ideal mixture of the real fluids:

CO_2 - Span and Wagner
H_2O - IAPWS-95
N_2 - Span et al.
O_2 - Schmidt and Wagner
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 and 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 the VDI 4670
- Poynting effect from ASHRAE RP-1485

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

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 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	Ethyl alcohol
CH_3OH	Methyl alcohol
$C_3H_8O_3$	Glycerol
K_2CO_3	Potassium carbonate
$CaCl_2$	Calcium chloride
$MgCl_2$	Magnesium chloride
NaCl	Sodium chloride
$C_2H_3KO_2$	Potassium acetate

Formulation of the International Institute of Refrigeration (1997)

Ethanol
Library LibC2H5OH
Formulation of Schroeder (2012)

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
Library LibN2
Formulation of
Span et al. (2000)

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**
Dinitrogen monooxide N_2O **Library LibN2O**
Sulfur dioxide SO_2 **Library LibSO2**
Acetone C_3H_6O **Library LibC3H6O**
Formulation of Lemmon and Span (2006)

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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

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 can be calculated.

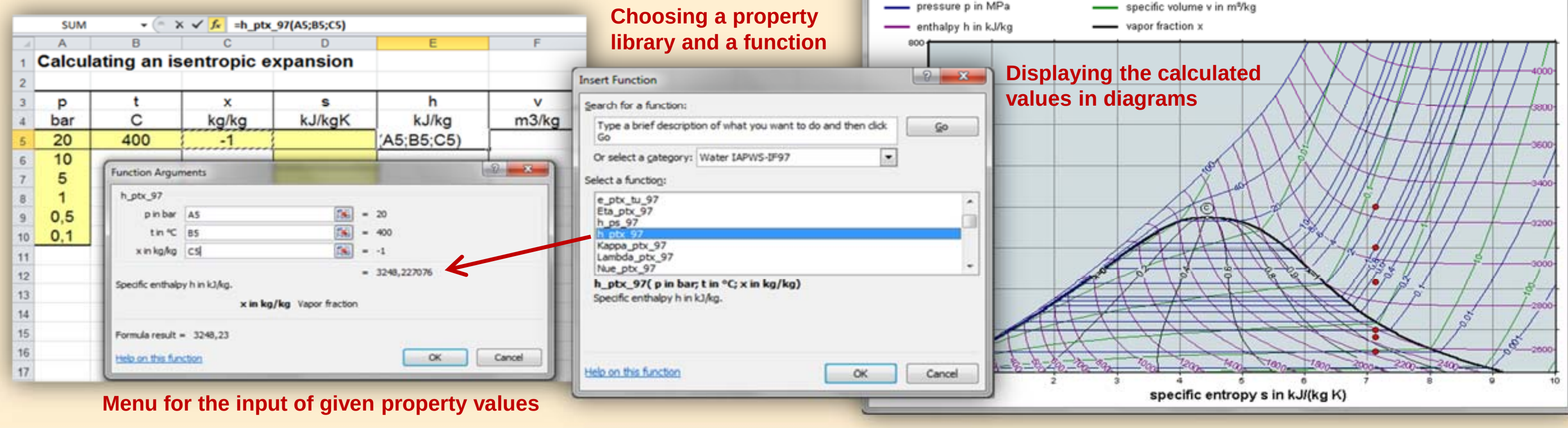
[a] Not all of these property functions are available in all property libraries.

www.thermodynamic-property-libraries.com

ZITTAU/GOERLITZ UNIVERSITY OF APPLIED SCIENCES
Department of Technical Thermodynamics
www.thermodynamics-zittau.de

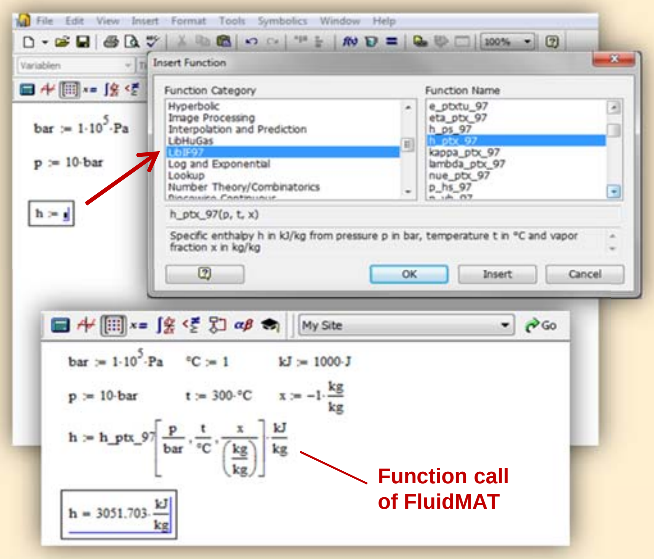
Property Software for Calculating Heat Cycles, Boilers, Turbines and Refrigerators

Add-In FluidEXL*Graphics* for Excel®



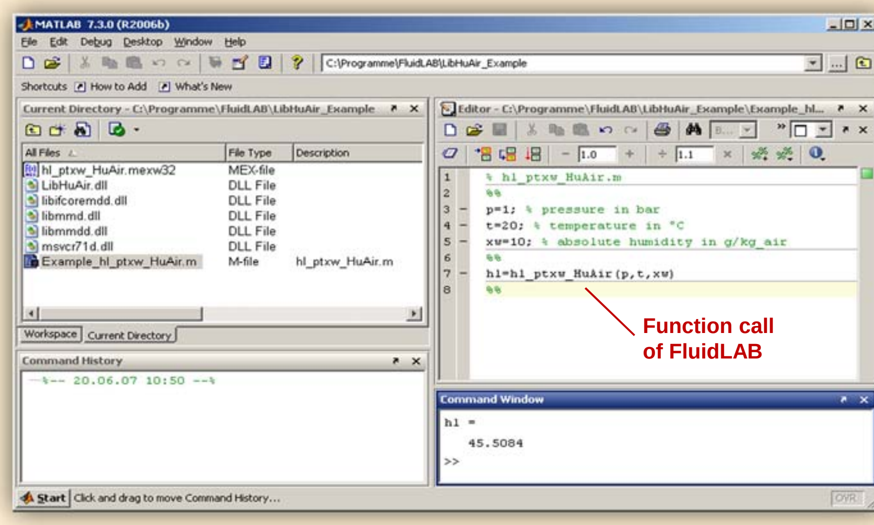
Add-In FluidMAT for Mathcad®

The property libraries can be used in Mathcad®.



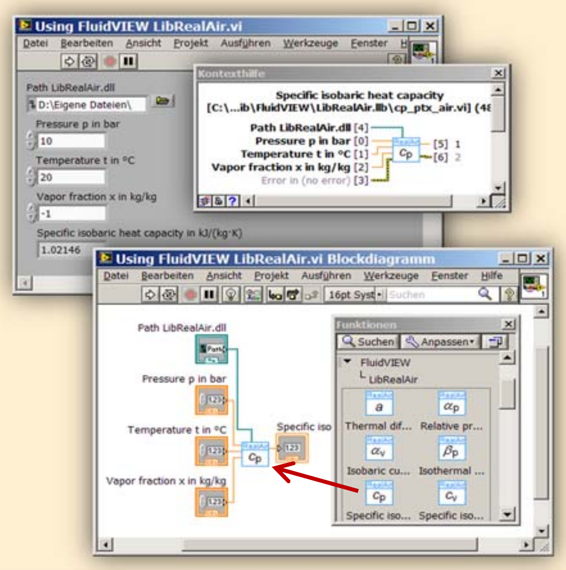
Add-In FluidLAB for MATLAB®

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



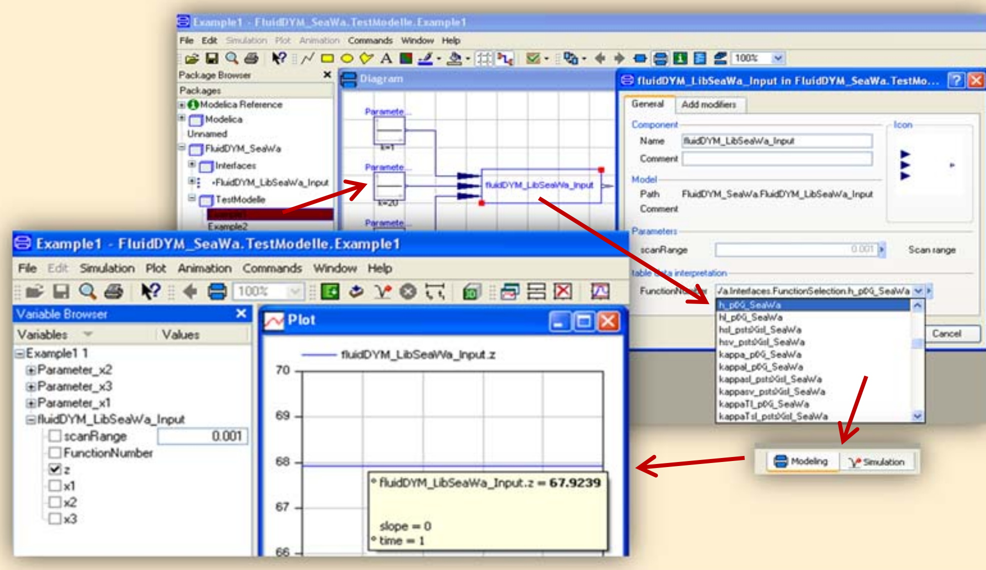
Add-On FluidVIEW for LabVIEW®

The property functions can be calculated in LabVIEW®.

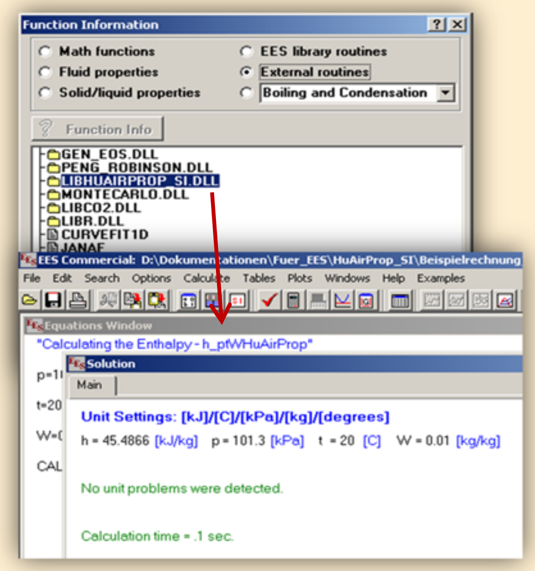


Add-In FluidDYM for DYMOLA® (Modelica) and SimulationX®

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

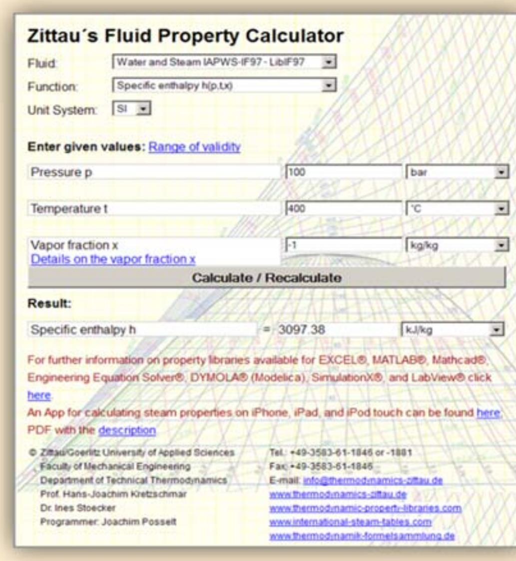


Add-In **FluidEES** for Engineering Equation Solver®



App International Steam Tables for iPhone, iPad, iPod touch, Android smart phones and tablets

Online Property Calculator at www.thermodynamics-zittau.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

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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

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 can be calculated.

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

www.thermodynamic-property-libraries.com

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