Humid Air Properties

Contents

If you are feeling impatient, jump to Sample HAPropsSI Code, or to go to the code documentation `CoolProp.HumidAirProp`, otherwise, hang in there.

The equations implemented in CoolProp are based on a publication by Hermann et al. [161], which describes the outcome of the ASHRAE research project ASHREA-RP1485. The same source has been used in the ASHRAE Handbook 2009 to generate reference saturation property tables. The code implemented here passes all tests and reproduces the original data with a very high accuracy. It is applicable for pressure from 0.01 kPa up to 10 MPa, in a temperature range from -143.15 °C up to 350 °C with a humidity ratio from 0 kg of water up to 10 kg of water per kg of dry air.

Humid air can be modeled as a mixture of air and water vapor. In the simplest analysis, water and air are treated as ideal gases but in principle there is interaction between the air and water molecules that must be included through the use of interaction parameters.

Because humid air is a mixture of dry air (treated as a pseudo-pure gas) and water vapor (treated as a real gas), three variables are required to fix the state by the state postulate.

In the analysis that follows, the three parameters that are ultimately needed to calculate everything else are the dry bulb temperature T, the total pressure p, and the molar fraction of water ψ_w. The molar fraction of air is simply $\psi_a = 1 - \psi_w$.

Of course, it is not so straightforward to measure the mole fraction of water vapor molecules, so other measures are used. There are three different variables that can be used to obtain the mole fraction of water vapor without resorting to iterative methods.

1. Humidity ratio

The humidity ratio W is the ratio of the mass of water vapor to the mass of air in the mixture. Thus the mole fraction of water can be obtained from

$$\psi_w = \frac{n_w}{n} = \frac{n_w}{n_a + n_w} = \frac{m_w/M_w}{m_a/M_a + m_w/M_w} = \frac{m_w}{(M_w/M_a)m_a + m_w} = \frac{1}{(M_w/M_a)/W + 1} = \frac{W}{(M_w/M_a) + W}$$

or

$$\psi_w = \frac{W}{\varepsilon + W}$$

where the ratio of mole masses ε is given by $\varepsilon = M_w/M_a$

2. Relative Humidity

The relative humidity φ is defined as the ratio of the mole fraction of water in the humid air to the saturation mole fraction of water. Because of the presence of air with the water, the pure water saturated vapor pressure $p_{w,s}$ must be multiplied by an enhancement factor f that is very close to one near atmospheric conditions.

Mathematically, the result is

$$\varphi = \frac{\psi_w}{\psi_{w,s}}$$

where

$$\psi_{w,s} = \frac{fp_{w,s}}{p}$$

The product p_s is defined by $p_s = fp_{w,s}$, and $p_{w,s}$ is the saturation pressure of pure water (or ice) at temperature T. This yields the result for ψ_w of

$$\varphi = \frac{\psi_w}{p_s/p}$$
$$\psi_w = \frac{\varphi p_s}{p}$$

3. Dewpoint temperature

The dewpoint temperature is defined as the temperature at which the actual vapor pressure of water is equal to the saturation vapor pressure. At the given dewpoint, the vapor pressure of water is given by

$$p_w = f(p, T_{dp}) p_{w,s}(T_{dp})$$

and the mole fraction of water vapor is obtained from

$$\psi_w = \frac{p_w}{p}$$

Once the state has been fixed by a set of T, p, ψ_w, any parameter of interest can be calculated

Molar Volume

$$p = \frac{\bar{R}T}{\bar{v}}\left(1 + \frac{B_m}{\bar{v}} + \frac{C_m}{\bar{v}^2}\right) \tag{1}$$

The bracketed term on the right hand side is the compressibility Z factor, equal to 1 for ideal gas, and is a measure of non-ideality of the air. The virial terms are given by

$$B_m = (1-\psi_w)^2 B_{aa} + 2(1-\psi_w)\psi_w B_{aw} + \psi_w^2 B_{ww}$$
$$C_m = (1-\psi_w)^3 C_{aaa} + 3(1-\psi_w)^2 \psi_w C_{aaw} + 3(1-\psi_w)\psi_w^2 C_{aww} + \psi_w^3 C_{www}$$

where the virial coefficients are described in ASRAE RP-1485 and their values are provided in Humid Air Validation. All virial terms are functions only of temperature.

Usually the temperature is known, the water mole fraction is calculated, and $\bar{v}$ is found using iterative methods, in HAProps, using a secant solver and the first guess that the compressibility factor is 1.0.

Molar Enthalpy

The molar enthalpy of humid air is obtained from

$$\bar{h} = (1-\psi_w)\bar{h}_a^o + \psi_w \bar{h}_w^o + \bar{R}T\left[(B_m - T\frac{dB_m}{dT})\frac{1}{\bar{v}} + \left(C_m - \frac{T}{2}\frac{dC_m}{dT}\right)\frac{1}{\bar{v}^2}\right]$$

with $\bar{h}$ in kJ/kmol. For both air and water, the full EOS is used to evaluate the enthalpy

$$\bar{h}_a^o = \bar{h}_0 + \bar{R}T\left[1 + \tau\left(\frac{\partial \alpha^o}{\partial \tau}\right)_\delta\right]$$

which is in kJ/kmol, using the mixture $\bar{v}$ to define the parameter $\delta = 1/(\bar{v}\bar{\rho}_c)$ for each fluid, and using the critical molar density for the fluid obtained from $\bar{\rho}_c = 1000\rho_c/M$ to give units of mol/m^3. The offset enthalpies for air and water are given by

$$\bar{h}_{0,a} = -7{,}914.149298 \text{ kJ/kmol}$$
$$\bar{h}_{0,w} = -0.01102303806 \text{ kJ/kmol}$$

respectively. The enthalpy per kg of dry air is given by

$$h = \bar{h}\frac{1+W}{M_{ha}}$$

Enhancement factor

The enhancement factor is a parameter that includes the impact of the air on the saturation pressure of water vapor. It is only a function of temperature and pressure, but it must be iteratively obtained due to the nature of the expression for the enhancement factor.

$\psi_{w,s}$ is given by $\psi_{w,s} = f p_{w,s}/p$, where f can be obtained from

$$\ln(f) = \left[\begin{array}{l} \left[\dfrac{(1+k_T p_{w,s})(p-p_{w,s}) - k_T \dfrac{(p^2 - p_{w,s}^2)}{2}}{\bar{R}T}\right] \bar{v}_{w,s} + \ln[1-\beta_H(1-\psi_{w,s})p] \\ + \left[\dfrac{(1-\psi_{w,s})^2 p}{\bar{R}T}\right] B_{aa} - 2\left[\dfrac{(1-\psi_{w,s})^2 p}{\bar{R}T}\right] B_{aw} - \left[\dfrac{(p-p_{w,s}-(1-\psi_{w,s})^2 p)}{\bar{R}T}\right] B_{ww} \\ + \left[\dfrac{(1-\psi_{w,s})^3 p^2}{(\bar{R}T)^2}\right] C_{aaa} + \left[\dfrac{3(1-\psi_{w,s})^2[1-2(1-\psi_{w,s})]p^2}{2(\bar{R}T)^2}\right] C_{aaw} \\ - \left[\dfrac{3(1-\psi_{w,s})^2 \psi_{w,s} p^2}{(\bar{R}T)^2}\right] C_{aww} - \left[\dfrac{(3-2\psi_{w,s})\psi_{w,s}^2 p^2 - p_{w,s}^2}{2(\bar{R}T)^2}\right] C_{www} \\ - \left[\dfrac{(1-\psi_{w,s})^2(-2+3\psi_{w,s})\psi_{w,s} p^2}{(\bar{R}T)^2}\right] B_{aa} B_{ww} \\ - \left[\dfrac{2(1-\psi_{w,s})^3(-1+3\psi_{w,s})p^2}{(\bar{R}T)^2}\right] B_{aa} B_{aw} \\ + \left[\dfrac{6(1-\psi_{w,s})^2 \psi_{w,s}^2 p^2}{(\bar{R}T)^2}\right] B_{ww} B_{aw} - \left[\dfrac{3(1-\psi_{w,s})^4 p^2}{2(\bar{R}T)^2}\right] B_{aa}^2 \\ - \left[\dfrac{2(1-\psi_{w,s})^2 \psi_{w,s}(-2+3\psi_{w,s})p^2}{(\bar{R}T)^2}\right] B_{aw}^2 - \left[\dfrac{p_{w,s}^2 - (4-3\psi_{w,s})(\psi_{w,s})^3 p^2}{2(\bar{R}T)^2}\right] B_{ww}^2 \end{array}\right]$$

Isothermal Compressibility

For water, the isothermal compressibility [in 1/Pa] is evaluated from

$$k_T = \frac{1}{\rho \frac{\partial p}{\partial \rho}} \frac{1\ \text{kPa}}{1000\ \text{Pa}}$$

with

$$\frac{\partial p}{\partial \rho} = RT\left[1 + 2\delta\left(\frac{\partial \alpha^r}{\partial \delta}\right)_\tau + \delta^2\left(\frac{\partial^2 \alpha^r}{\partial \delta^2}\right)_\tau\right]$$

in kPa/(kg/m^3). And for ice,

$$k_T = \left(\frac{\partial^2 g}{\partial p^2}\right)\left(\frac{\partial g}{\partial p}\right)_T^{-1} \frac{1\ \text{kPa}}{1000\ \text{Pa}}$$

Sample HAPropsSI Code

To use the HAPropsSI function, import it and do some calls, do something like this

```
#import the things you need
In [1]: from CoolProp.HumidAirProp import HAPropsSI

#Enthalpy (J per kg dry air) as a function of temperature, pressure,
#    and relative humidity at dry bulb temperature T of 25C, pressure
#    P of one atmosphere, relative humidity R of 50%
In [2]: h = HAPropsSI('H','T',298.15,'P',101325,'R',0.5); print(h)
50423.45039107799

#Temperature of saturated air at the previous enthalpy
In [3]: T = HAPropsSI('T','P',101325,'H',h,'R',1.0); print(T)
290.9620924692057

#Temperature of saturated air - order of inputs doesn't matter
In [4]: T = HAPropsSI('T','H',h,'R',1.0,'P',101325); print(T)
290.9620924692057
```

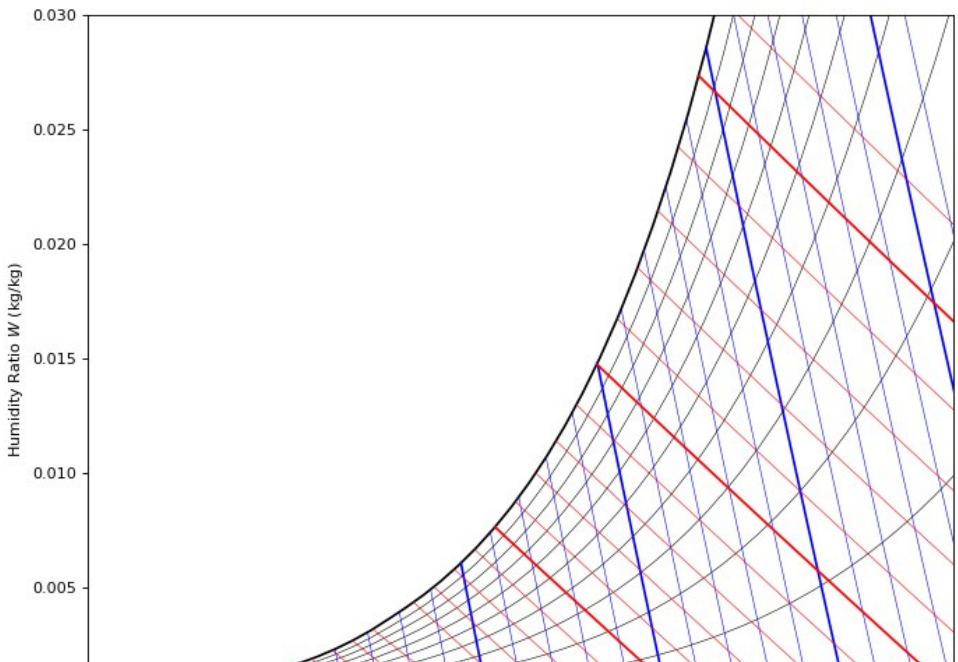
Table of Inputs/Outputs to HAPropsSI

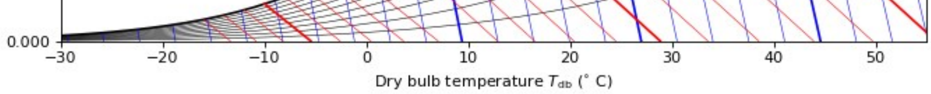
Input/Output parameters

Parameter	Units	Input/Output	Description
`B`, `Twb`, `T_wb`, `WetBulb`	K	Input/Output	Wet-Bulb Temperature
`C`, `cp`	J/kg dry air/K	Output	Mixture specific heat per unit dry air
`Cha`, `cp_ha`	J/kg humid air/K	Output	Mixture specific heat per unit humid air
`CV`	J/kg dry air/K	Output	Mixture specific heat at constant volume per unit dry air
`CVha`, `cv_ha`	J/kg humid air/K	Output	Mixture specific heat at constant volume per unit humid air
`D`, `Tdp`, `DewPoint`, `T_dp`	K	Input/Output	Dew-Point Temperature
`H`, `Hda`, `Enthalpy`	J/kg dry air	Input/Output	Mixture enthalpy per dry air
`Hha`	J/kg humid air	Input/Output	Mixture enthalpy per humid air
`K`, `k`, `Conductivity`	W/m/K	Output	Mixture thermal conductivity
`M`, `Visc`, `mu`	Pa-s	Output	Mixture viscosity
`psi_w`, `Y`	mol water/mol humid air	Input/Output	Water mole fraction
`P`	Pa	Input	Pressure
`P_w`	Pa	Input	Partial pressure of water vapor
`R`, `RH`, `RelHum`		Input/Output	Relative humidity in [0, 1]
`S`, `Sda`, `Entropy`	J/kg dry air/K	Input/Output	Mixture entropy per unit dry air
`Sha`	J/kg humid air/K	Input/Output	Mixture entropy per unit humid air
`T`, `Tdb`, `T_db`	K	Input/Output	Dry-Bulb Temperature
`V`, `Vda`	m^3/kg dry air	Input/Output	Mixture volume per unit dry air
`Vha`	m^3/kg humid air	Input/Output	Mixture volume per unit humid air
`W`, `Omega`, `HumRat`	kg water/kg dry air	Input/Output	Humidity Ratio
`Z`		Output	Compressibility factor ($Z = pv/(RT)$)

Psychrometric Chart

(Source code, png, .pdf)





Humid Air Validation

Values here are obtained at documentation build-time using the Humid Air Properties module

```
In [5]: %run 'fluid_properties/Validation/HAValidation.py'
 Replicating the tables from ASHRAE RP-1485

A.6.1 Psychrometric Properties of Moist Air at 0C and Below
Saturated air at 101.325 kPa
====================================================
   T         Ws         v       h         s
   C      kgw/kg_da   m3/kgda  kJ/kgda  kJ/kgda/K
----------------------------------------------------
     -60 0.0000067    0.6027   -60.325   -0.2494
     -55 0.0000129    0.6169   -55.280   -0.2260
     -50 0.0000243    0.6312   -50.222   -0.2030
     -45 0.0000445    0.6454   -45.144   -0.1805
     -40 0.0000793    0.6597   -40.031   -0.1583
     -35 0.0001379    0.6740   -34.859   -0.1364
     -30 0.0002345    0.6883   -29.593   -0.1145
     -25 0.0003905    0.7027   -24.181   -0.0924
     -20 0.0006373    0.7172   -18.542   -0.0699
     -15 0.0010207    0.7319   -12.560   -0.0465
     -10 0.0016062    0.7468    -6.070   -0.0215
      -5 0.0024863    0.7622     1.165    0.0057
       0 0.0037900    0.7780     9.475    0.0364
====================================================

A.6.2 Psychrometric Properties of Moist Air at 0C and Above
Saturated air at 101.325 kPa
====================================================
   T         Ws         v       h         s
   C      kgw/kg_da   m3/kgda  kJ/kgda  kJ/kgda/K
----------------------------------------------------
       0 0.0037900     0.778      9.47    0.0364
       5 0.0054247     0.794     18.64    0.0697
      10 0.0076626     0.812     29.35    0.1079
      15 0.0106938     0.830     42.12    0.1525
      20 0.0147605     0.850     57.56    0.2057
      25 0.0201734     0.872     76.50    0.2699
      30 0.0273329     0.896    100.01    0.3482
      35 0.0367601     0.924    129.46    0.4448
      40 0.0491445     0.957    166.69    0.5650
      45 0.0654161     0.995    214.17    0.7162
      50 0.0868629     1.042    275.35    0.9081
      55 0.1153262     1.101    355.15    1.1549
      60 0.1535446     1.175    460.89    1.4776
      65 0.2057936     1.273    604.00    1.9084
      70 0.2791668     1.405    803.48    2.5012
      75 0.3863984     1.593   1093.39    3.3518
      80 0.5529259     1.881   1541.79    4.6511
      85 0.8381052     2.367   2307.52    6.8431
      90 1.4202351     3.349   3867.63   11.2559
====================================================

A.8.1 Psychrometric Properties of Moist Air at 101.325 kPa
Dry Bulb temperature of 200C
================================================================
      W        Twb         v       h          s          RH
  kgw/kg_da     C       m3/kgda  kJ/kgda  kJ/kgda/K     %
----------------------------------------------------------------
      0.00     45.07     1.341    202.52    0.5558    0.0000
      0.05     55.38     1.448    346.49    1.0299    0.4850
      0.10     61.85     1.556    490.43    1.4736    0.9028
      0.20     69.95     1.771    778.25    2.3337    1.5859
      0.30     75.00     1.986   1066.01    3.1752    2.1208
      0.40     78.51     2.201   1353.73    4.0059    2.5510
      0.50     81.12     2.416   1641.42    4.8295    2.9045
      0.60     83.14     2.630   1929.09    5.6479    3.2002
      0.70     84.76     2.845   2216.73    6.4624    3.4511
      0.80     86.09     3.060   2504.37    7.2737    3.6668
      0.90     87.20     3.274   2791.99    8.0824    3.8541
      1.00     88.15     3.489   3079.60    8.8891    4.0183
================================================================

A.8.2 Psychrometric Properties of Moist Air at 1000 kPa
Dry Bulb temperature of 200C
================================================================
      W        Twb         v       h          s          RH
  kgw/kg_da     C       m3/kgda  kJ/kgda  kJ/kgda/K     %
----------------------------------------------------------------
      0.00     90.47     0.136    201.94   -0.1033    0.0000
      0.05    107.30     0.147    345.60    0.3175    4.7863
```

0.10	117.69	0.158	488.97	0.7078	8.9096
0.20	180.72	0.179	775.07	1.4603	15.6512
0.30	138.66	0.200	1060.53	2.1936	20.9304
0.40	144.29	0.222	1345.53	2.9157	25.1764
0.50	148.49	0.243	1630.17	3.6303	28.6655
0.60	151.76	0.264	1914.54	4.3394	31.5835
0.70	154.39	0.284	2198.70	5.0443	34.0601
0.80	156.56	0.305	2482.69	5.7459	36.1883
0.90	158.37	0.326	2766.53	6.4448	38.0369
1.00	159.92	0.347	3050.26	7.1414	39.6575

A.8.3 Psychrometric Properties of Moist Air at 2000 kPa
Dry Bulb temperature of 200C

W kgw/kg_da	Twb C	v m3/kgda	h kJ/kgda	s kJ/kgda/K	RH %
0.00	105.93	0.068	201.34	-0.3045	0.0000
0.05	125.81	0.074	344.62	0.1000	9.3475
0.10	138.03	0.079	487.33	0.4735	17.4003
0.20	153.19	0.089	771.38	1.1917	30.5666
0.30	162.65	0.100	1054.03	1.8898	40.8768
0.40	169.28	0.110	1335.64	2.5761	49.1691
0.50	174.23	0.120	1616.43	3.2542	55.9833
0.60	178.11	0.130	1896.58	3.9265	61.6822
0.70	181.23	0.140	2176.21	4.5942	66.5189
0.80	183.81	0.150	2455.41	5.2582	70.6753
0.90	185.98	0.160	2734.26	5.9193	74.2855
1.00	187.83	0.169	3012.79	6.5780	77.4505

A.8.4 Psychrometric Properties of Moist Air at 5000 kPa
Dry Bulb temperature of 200C

W kgw/kg_da	Twb C	v m3/kgda	h kJ/kgda	s kJ/kgda/K	RH %
0.00	126.87	0.028	199.72	-0.5738	0.0000
0.05	151.76	0.030	341.85	-0.1918	21.5445
0.10	166.94	0.032	482.37	0.1580	40.1047
0.15	177.63	0.034	621.47	0.4958	56.2606
0.20	185.72	0.036	759.34	0.8257	70.4509
0.25	192.15	0.037	896.09	1.1499	83.0138
0.30	197.42	0.039	1031.82	1.4695	94.2140

A.8.5 Psychrometric Properties of Moist Air at 10,000 kPa
Dry Bulb temperature of 200C

W kgw/kg_da	Twb C	v m3/kgda	h kJ/kgda	s kJ/kgda/K	RH %
0.00	142.19	0.014	197.66	-0.7823	0.0000
0.05	171.31	0.015	337.69	-0.4188	39.4620
0.10	188.92	0.016	473.92	-0.0901	73.4579

A.9.1 Psychrometric Properties of Moist Air at 101.325 kPa
Dry Bulb temperature of 320C

W kgw/kg_da	Twb C	v m3/kgda	h kJ/kgda	s kJ/kgda/K	RH %
0.00	54.90	1.681	326.93	0.7901	0.0000
0.05	62.07	1.816	482.76	1.2864	0.0668
0.10	67.00	1.951	638.59	1.7525	0.1244
0.20	73.54	2.221	950.21	2.6573	0.2185
0.30	77.79	2.491	1261.80	3.5436	0.2922
0.40	80.80	2.761	1573.37	4.4192	0.3515
0.50	83.07	3.030	1884.93	5.2876	0.4002
0.60	84.85	3.300	2196.47	6.1509	0.4409
0.70	86.28	3.570	2508.01	7.0102	0.4755
0.80	87.46	3.840	2819.54	7.8664	0.5052
0.90	88.45	4.109	3131.07	8.7200	0.5310
1.00	89.29	4.379	3442.59	9.5715	0.5536

A.9.2 Psychrometric Properties of Moist Air at 1000 kPa
Dry Bulb temperature of 320C

W kgw/kg_da	Twb C	v m3/kgda	h kJ/kgda	s kJ/kgda/K	RH %
0.00	107.70	0.171	326.80	0.1318	0.0000
0.05	118.99	0.185	482.46	0.5751	0.6594
0.10	126.74	0.198	637.99	0.9880	1.2275
0.20	137.03	0.225	948.77	1.7865	2.1564
0.30	143.73	0.252	1259.26	2.5661	2.8838
0.40	148.52	0.279	1569.56	3.3350	3.4688
0.50	152.14	0.306	1879.70	4.0966	3.9495
0.60	154.99	0.333	2189.73	4.8529	4.3515
0.70	157.29	0.360	2499.68	5.6053	4.6927
0.80	159.19	0.387	2809.55	6.3544	4.9860

0.90	160.79	0.414	3119.37	7.1010	5.2407
1.00	162.16	0.441	3429.15	7.8454	5.4639

A.9.3 Psychrometric Properties of Moist Air at 2000 kPa
Dry Bulb temperature of 320C

W kgw/kg_da	Twb C	v m3/kgda	h kJ/kgda	s kJ/kgda/K	RH %
0.00	126.92	0.086	326.68	-0.0685	0.0000
0.05	140.12	0.093	482.14	0.3587	1.3189
0.10	149.16	0.099	637.35	0.7553	2.4551
0.20	161.20	0.113	947.16	1.5209	4.3128
0.30	169.07	0.126	1256.41	2.2675	5.7675
0.40	174.71	0.140	1565.23	3.0031	6.9375
0.50	178.98	0.153	1873.75	3.7313	7.8990
0.60	182.35	0.166	2182.04	4.4542	8.7031
0.70	185.08	0.179	2490.14	5.1730	9.3855
0.80	187.34	0.192	2798.09	5.8886	9.9719
0.90	189.25	0.206	3105.93	6.6015	10.4813
1.00	190.88	0.219	3413.67	7.3123	10.9279

A.9.4 Psychrometric Properties of Moist Air at 5000 kPa
Dry Bulb temperature of 320C

W kgw/kg_da	Twb C	v m3/kgda	h kJ/kgda	s kJ/kgda/K	RH %
0.00	154.63	0.035	326.46	-0.3351	0.0000
0.05	170.96	0.037	481.31	0.0702	3.2972
0.10	182.17	0.040	635.49	0.4448	6.1377
0.15	190.55	0.043	789.13	0.8084	8.6103
0.20	197.14	0.045	942.31	1.1653	10.7820
0.25	202.51	0.048	1095.11	1.5175	12.7047
0.30	206.99	0.050	1247.59	1.8662	14.4188
0.40	214.09	0.056	1551.73	2.5554	17.3438
0.50	219.52	0.061	1855.02	3.2369	19.7474
0.60	223.82	0.066	2157.63	3.9126	21.7577
0.70	227.33	0.071	2459.71	4.5840	23.4637
0.80	230.25	0.076	2761.36	5.2518	24.9298
0.90	232.72	0.081	3062.64	5.9169	26.2033
1.00	234.85	0.085	3363.63	6.5796	27.3197

A.9.5 Psychrometric Properties of Moist Air at 10,000 kPa
Dry Bulb temperature of 320C

W kgw/kg_da	Twb C	v m3/kgda	h kJ/kgda	s kJ/kgda/K	RH %
0.00	176.72	0.018	326.51	-0.5397	0.0000
0.05	195.85	0.019	480.31	-0.1514	6.5945
0.10	209.00	0.020	632.70	0.2054	12.2755
0.15	218.85	0.022	783.90	0.5507	17.2206
0.20	226.63	0.023	934.12	0.8889	21.5640
0.25	233.00	0.024	1083.47	1.2220	25.4093
0.30	238.33	0.025	1232.08	1.5512	28.8376
0.40	246.84	0.028	1527.40	2.2005	34.6877
0.50	253.40	0.030	1820.61	2.8409	39.4949
0.60	258.63	0.032	2112.08	3.4747	43.5153
0.70	262.94	0.034	2402.10	4.1033	46.9275
0.80	266.55	0.036	2690.88	4.7277	49.8597
0.90	269.63	0.039	2978.59	5.3487	52.4066
1.00	272.29	0.041	3265.36	5.9667	54.6395

Pure fluid Virial Coefficients

T	Baa	Caaa	Bww	Cwww
C	b'm^3/mol'	b'm^6/mol^2'	b'm^3/mol\x002'	b'm^6/mol^2'
-60.0	-3.3064504913e-05	2.1778728776e-09	-1.1174019230e-02	-1.5162998768e-04
-50.0	-2.8932056455e-05	2.1163810315e-09	-7.8721344601e-03	-8.7876439931e-05
-40.0	-2.5223205510e-05	2.0616570944e-09	-5.7127237936e-03	-5.5471167065e-05
-30.0	-2.1877241883e-05	2.0127116499e-09	-4.2586206439e-03	-3.6054467433e-05
-20.0	-1.8844568169e-05	1.9687328800e-09	-3.2532396168e-03	-2.3880058317e-05
-10.0	-1.6084254149e-05	1.9290492160e-09	-2.5411800904e-03	-1.6072254169e-05
0.0	-1.3562212432e-05	1.8931009119e-09	-2.0256198165e-03	-1.0976416841e-05
10.0	-1.1249818308e-05	1.8604181700e-09	-1.6446680868e-03	-7.5982156425e-06
20.0	-9.1228522265e-06	1.8306041394e-09	-1.3578320706e-03	-5.3262047265e-06
30.0	-7.1606799362e-06	1.8033215779e-09	-1.1380508933e-03	-3.7775456074e-06
40.0	-5.3456100212e-06	1.7782822977e-09	-9.6688526113e-04	-2.7086426379e-06
50.0	-3.6623854498e-06	1.7552387450e-09	-8.3154379347e-04	-1.9621726463e-06
60.0	-2.0977774966e-06	1.7339772333e-09	-7.2300490095e-04	-1.4351072804e-06
70.0	-6.4025867871e-07	1.7143124658e-09	-6.3480699108e-04	-1.0590893108e-06
80.0	7.2026273739e-07	1.6960830728e-09	-5.6225490863e-04	-7.8820574569e-07
90.0	1.9926598215e-06	1.6791479533e-09	-5.0189060427e-04	-5.9126044774e-07
100.0	3.1847656914e-06	1.6633832580e-09	-4.5113452236e-04	-4.4682462927e-07
110.0	4.3035215681e-06	1.6486798883e-09	-4.0803910950e-04	-3.4002636972e-07
120.0	5.3551001609e-06	1.6349414114e-09	-3.7111708564e-04	-2.6044318239e-07
130.0	6.3450090665e-06	1.6220823143e-09	-3.3922027793e-04	-2.0070296438e-07
140.0	7.2781778723e-06	1.6100265349e-09	-3.1145310612e-04	-1.5554524200e-07
150.0	8.1590318924e-06	1.5987062200e-09	-2.8711011151e-04	-1.2118485357e-07

160.0	8.9915548780e-06	1.5880606719e-09	-2.6563036496e-04	-9.4876457701e-08
170.0	9.7793425843e-06	1.5780354497e-09	-2.4656385529e-04	-7.4613740198e-08
180.0	1.0525648716e-05	1.5685816023e-09	-2.2954647025e-04	-5.8919833627e-08
190.0	1.1233424489e-05	1.5596550080e-09	-2.1428120144e-04	-4.6700067957e-08
200.0	1.1905352827e-05	1.5512158075e-09	-2.0052390022e-04	-3.7137687457e-08

T	Baw	Caaw	Caww
C	b'm^3/mol\x002'	b'm^6/mol^2'	b'm^6/mol^2'
-60.0	-6.8305808721e-05	1.0273000716e-09	-1.8214316825e-06
-50.0	-6.1680233064e-05	1.0001595421e-09	-1.1787612409e-06
-40.0	-5.5836203092e-05	9.7107903308e-10	-7.9593677251e-07
-30.0	-5.0645881561e-05	9.4180678583e-10	-5.5678343751e-07
-20.0	-4.6007498746e-05	9.1337025409e-10	-4.0128618357e-07
-10.0	-4.1839118849e-05	8.8634392341e-10	-2.9668474376e-07
0.0	-3.8074090909e-05	8.6101819497e-10	-2.2423408862e-07
10.0	-3.4657682115e-05	8.3750672364e-10	-1.7276396504e-07
20.0	-3.1544553729e-05	8.1581500536e-10	-1.3537862024e-07
30.0	-2.8696845981e-05	7.9588431449e-10	-1.0768721224e-07
40.0	-2.6082708793e-05	7.7761982700e-10	-8.6816421215e-08
50.0	-2.3675162869e-05	7.6090853025e-10	-7.0839762898e-08
60.0	-2.1451208360e-05	7.4563050528e-10	-5.8437245597e-08
70.0	-1.9391120996e-05	7.3166589756e-10	-4.8686625860e-08
80.0	-1.7477891584e-05	7.1889908286e-10	-4.0932107713e-08
90.0	-1.5696776156e-05	7.0722101405e-10	-3.4699849863e-08
100.0	-1.4034932249e-05	6.9653039669e-10	-2.9642457363e-08
110.0	-1.2481122776e-05	6.8673412025e-10	-2.5501820730e-08
120.0	-1.1025473368e-05	6.7774722643e-10	-2.2083805133e-08
130.0	-9.6592722783e-06	6.6949259959e-10	-1.9240735645e-08
140.0	-8.3748044505e-06	6.6190050073e-10	-1.6859099163e-08
150.0	-7.1652131416e-06	6.5490802360e-10	-1.4850792059e-08
160.0	-6.0243839304e-06	6.4845852337e-10	-1.3146812982e-08
170.0	-4.9468470096e-06	6.4250104926e-10	-1.1692664630e-08
180.0	-3.9276944932e-06	6.3698980018e-10	-1.0444965002e-08
190.0	-2.9625101219e-06	6.3188361380e-10	-9.3689246298e-09
200.0	-2.0473092535e-06	6.2714549461e-10	-8.4364506623e-09

Pure fluid Virial Coefficients Derivatives

T	dBaa	dCaaa	dBww	dCwww
C	b'm^3/mol\x002'	b'm^6/mol^2'	b'm^3/mol\x002'	b'm^6/mol^2'
-60.0	4.3678901718e-07	-6.5259421081e-12	4.0907134267e-04	9.7890225556e-06
-50.0	3.9094567047e-07	-5.7925951449e-12	2.6368394754e-04	4.2599502143e-06
-40.0	3.5183089770e-07	-5.1686009316e-12	1.7524578197e-04	2.4534392599e-06
-30.0	3.1818443574e-07	-4.6339568007e-12	1.1972698408e-04	1.5168064804e-06
-20.0	2.8902947780e-07	-4.1729431726e-12	8.3872099442e-05	9.6398589135e-07
-10.0	2.6359917737e-07	-3.7730826593e-12	6.0116039515e-05	6.2432365587e-07
0.0	2.4128450184e-07	-3.4243800668e-12	4.4005975878e-05	4.1098205932e-07
10.0	2.2159662973e-07	-3.1187604739e-12	3.2846510930e-05	2.7460401649e-07
20.0	2.0413943007e-07	-2.8496489141e-12	2.4963984884e-05	1.8603615349e-07
30.0	1.8858904489e-07	-2.6116525842e-12	1.9294782853e-05	1.2767075965e-07
40.0	1.7467855065e-07	-2.4003181623e-12	1.5148499662e-05	8.8680535853e-08
50.0	1.6218630137e-07	-2.2119447569e-12	1.2068194612e-05	6.2299015990e-08
60.0	1.5092697458e-07	-2.0434384795e-12	9.7459891450e-06	4.4233623231e-08
70.0	1.4074462510e-07	-1.8921984596e-12	7.9709845791e-06	3.1722699778e-08
80.0	1.3150724657e-07	-1.7560268233e-12	6.5964818172e-06	2.2965936560e-08
90.0	1.2310247686e-07	-1.6330570877e-12	5.5189694206e-06	1.6775064043e-08
100.0	1.1543417961e-07	-1.5216968216e-12	4.6644255474e-06	1.2356543007e-08
110.0	1.0841970276e-07	-1.4205814367e-12	3.9792467564e-06	9.1745422056e-09
120.0	1.0198766459e-07	-1.3285367274e-12	3.4241524938e-06	6.8634353500e-09
130.0	9.6076153981e-08	-1.2445483295e-12	2.9700329278e-06	5.1712456914e-09
140.0	9.0631258338e-08	-1.1677366865e-12	2.5950842306e-06	3.9226742483e-09
150.0	8.5605852607e-08	-1.0973364250e-12	2.2828082790e-06	2.9946678537e-09
160.0	8.0958597486e-08	-1.0326792823e-12	2.0206000698e-06	2.3001072716e-09
170.0	7.6653106484e-08	-9.7317990685e-13	1.7987394663e-06	1.7768097568e-09
180.0	7.2657249944e-08	-9.1832399823e-13	1.6096642209e-06	1.3800452917e-09
190.0	6.8942570813e-08	-8.6765835911e-13	1.4474407409e-06	1.0773984832e-09
200.0	6.5483792067e-08	-8.2078251748e-13	1.3073752610e-06	8.4521088732e-10

T	dBaw	dCaaw	dCaww
C	b'm^3/mol\x002'	b'm^6/mol^2'	b'm^6/mol^2'
-60.0	7.0671067841e-07	-2.5329306643e-12	8.3652108680e-08
-50.0	6.2109405080e-07	-2.8479923244e-12	4.8634111869e-08
-40.0	5.4982837510e-07	-2.9396633262e-12	2.9766967562e-08
-30.0	4.8992187794e-07	-2.8980941059e-12	1.9020412856e-08
-20.0	4.3911281598e-07	-2.7799104397e-12	1.2604799172e-08
-10.0	3.9566848048e-07	-2.6206893674e-12	8.6179394263e-09
0.0	3.5824516845e-07	-2.4426731561e-12	6.0532052853e-09
10.0	3.2578908214e-07	-2.2596007123e-12	4.3529611359e-09
20.0	2.9746516934e-07	-2.0797672895e-12	3.1957227862e-09
30.0	2.7260533603e-07	-1.9079803096e-12	2.3895374649e-09
40.0	2.5067028507e-07	-1.7468190020e-12	1.8161835419e-09
50.0	2.3122106772e-07	-1.5974502672e-12	1.4008122071e-09
60.0	2.1389764536e-07	-1.4601590182e-12	1.0948500459e-09
70.0	1.9840257004e-07	-1.3346933582e-12	8.6606704976e-10
80.0	1.8448844334e-07	-1.2204888941e-12	6.9264384038e-10
90.0	1.7194819305e-07	-1.1168137618e-12	5.5953719449e-10
100.0	1.6060747132e-07	-1.0228614572e-12	4.5620187444e-10
110.0	1.5031866448e-07	-9.3780925812e-13	3.7513243420e-10
120.0	1.4095613794e-07	-8.6085397191e-13	3.1091182225e-10
130.0	1.3241243488e-07	-7.9123279439e-13	2.5957962745e-10
140.0	1.2459521736e-07	-7.2823445525e-13	2.1820572123e-10
150.0	1.1742478936e-07	-6.7120410110e-13	1.8459817415e-10
160.0	1.1083207914e-07	-6.1954421544e-13	1.5710036152e-10
170.0	1.0475698647e-07	-5.7271310484e-13	1.3444819325e-10
180.0	9.9147021510e-08	-5.3022196394e-13	1.1566843627e-10
190.0	9.3956178059e-08	-4.9163118437e-13	1.0000548446e-10

```
200.0      8.9143996459e-08     -4.5654633851e-13    8.6868060073e-11

Water saturation pressure p_ws [kPa]
T           p_ws
C           b'Pa\x00/mol^2'
-60.00     1.0813475449e+00
-30.00     3.8005139487e+01
0.00       6.1115347506e+02
30.00      4.2466883405e+03
60.00      1.9945801925e+04
90.00      7.0182360745e+04
120.00     1.9866539974e+05
150.00     4.7610138108e+05
180.00     1.0026345688e+06
210.00     1.9073906643e+06
240.00     3.3466518715e+06
270.00     5.5028394741e+06
300.00     8.5877083296e+06

Henry Constant (zero for T < 273.15 K)
T           beta_H
C           b'1/Pa\x00ol^2'
0.01       2.2594633839e-10
30.01      1.3058555542e-10
60.01      1.0117905765e-10
90.01      9.5497073897e-11
120.01     1.0310894778e-10
150.01     1.2209642969e-10
180.01     1.5416532918e-10
210.01     2.0384427379e-10
240.01     2.7939520108e-10
270.01     3.9586839028e-10
300.01     5.8396949465e-10

Isothermal Compressibility of water (kT) [1/Pa]
T          p = 101325.000 Pa   p = 200000.000 Pa   p = 500000.000 Pa   p = 1000000.000 Pa
-60.00     1.0771099108e-10    1.0770400843e-10    1.0768278304e-10    1.0764742021e-10
-30.00     1.1257575753e-10    1.1256891351e-10    1.1254810951e-10    1.1251344878e-10
0.00       1.1778484390e-10    1.1777815515e-10    1.1775782318e-10    1.1772394894e-10
30.00      1.0048218396e-03    1.0047775852e-03    1.0046431164e-03    1.0044192594e-03
60.00      1.0173376853e-03    1.0172931915e-03    1.0171579998e-03    1.0169329553e-03
90.00      1.0360937793e-03    1.0360454263e-03    1.0358985238e-03    1.0356540343e-03
120.00     1.7695003917e+00    1.0604394263e-03    1.0602707553e-03    1.0599901229e-03
150.00     1.9111838106e+00    9.5989413316e-01    1.0905701909e-03    1.0902325237e-03
180.00     2.0511819911e+00    1.0326461304e+00    4.0465521554e-01    1.9441817992e-01
210.00     2.1901914433e+00    1.1043221088e+00    4.3506032354e-01    2.1154168024e-01
240.00     2.3285841090e+00    1.1753398746e+00    4.6467604880e-01    2.2755082652e-01
270.00     2.4665706339e+00    1.2459309799e+00    4.9380122272e-01    2.4295534461e-01
300.00     2.6042765544e+00    1.3162310320e+00    5.2260279146e-01    2.5797921396e-01

Molar volume of saturated liquid water or ice (vbar_ws) [m^3/mol_H2O]
T          p = 101325.000 Pa   p = 200000.000 Pa   p = 500000.000 Pa   p = 1000000.000 Pa
-60.00     1.9483157215e-11    1.9482950148e-11    1.9482320703e-11    1.9481271948e-11
-30.00     1.9562306493e-11    1.9562089195e-11    1.9561428642e-11    1.9560328042e-11
0.00       1.9651836970e-11    1.9651608576e-11    1.9650914289e-11    1.9649757465e-11
30.00      1.8094773222e-05    1.8094773222e-05    1.8094773222e-05    1.8094773222e-05
60.00      1.8323837443e-05    1.8323837443e-05    1.8323837443e-05    1.8323837443e-05
90.00      1.8662959891e-05    1.8662959891e-05    1.8662959891e-05    1.8662959891e-05
120.00     1.9102048132e-05    1.9102048132e-05    1.9102048132e-05    1.9102048132e-05
150.00     1.9645709876e-05    1.9645709876e-05    1.9645709876e-05    1.9645709876e-05
180.00     2.0310359748e-05    2.0310359748e-05    2.0310359748e-05    2.0310359748e-05
210.00     2.1126885602e-05    2.1126885602e-05    2.1126885602e-05    2.1126885602e-05
240.00     2.2149039824e-05    2.2149039824e-05    2.2149039824e-05    2.2149039824e-05
270.00     2.3473849596e-05    2.3473849596e-05    2.3473849596e-05    2.3473849596e-05
300.00     2.5297523418e-05    2.5297523418e-05    2.5297523418e-05    2.5297523418e-05

Enhancement factor (f) [no units]
T          p = 101325.000 Pa   p = 200000.000 Pa   p = 500000.000 Pa   p = 1000000.000 Pa  p = 10000000.000 Pa
-60.00     1.0070775889e+00    1.0140339780e+00    1.0356182628e+00    1.0730973444e+00    2.2389383691e+00
-40.00     1.0056000404e+00    1.0110608386e+00    1.0279266142e+00    1.0569409210e+00    1.8450348547e+00
-20.00     1.0046363568e+00    1.0090315492e+00    1.0225621564e+00    1.0456875555e+00    1.6193678937e+00
0.00       1.0041972674e+00    1.0078137836e+00    1.0189177377e+00    1.0378059886e+00    1.4778432214e+00
40.00      1.0048337245e+00    1.0074421047e+00    1.0151963013e+00    1.0282275373e+00    1.3082436191e+00
80.00      1.0057272574e+00    1.0097059521e+00    1.0168897805e+00    1.0272924735e+00    1.2343415184e+00
120.00     1.0000000000e+00    1.0001669826e+00    1.0183856131e+00    1.0312270756e+00    1.2048250858e+00
160.00     1.0000000000e+00    1.0000000000e+00    1.0000000000e+00    1.0231647493e+00    1.2031653250e+00
200.00     1.0000000000e+00    1.0000000000e+00    1.0000000000e+00    1.0000000000e+00    1.2128825018e+00
250.00     1.0000000000e+00    1.0000000000e+00    1.0000000000e+00    1.0000000000e+00    1.1903236875e+00
300.00     1.0000000000e+00    1.0000000000e+00    1.0000000000e+00    1.0000000000e+00    1.0480338998e+00
350.00     1.0000000000e+00    1.0000000000e+00    1.0000000000e+00    1.0000000000e+00    1.0000000000e+00
```

Verification Script

This script, written in Python, should yield no failures:

```
import CoolProp.CoolProp as CP
import numpy as np
import itertools
from multiprocessing import Pool
CP.set_config_bool(CP.DONT_CHECK_PROPERTY_LIMITS, True)
```

```
def generate_values(TR,P=101325):
    """ Starting with T,R as inputs, generate all other values """
    T,R = TR
    psi_w = CP.HAPropsSI('psi_w','T',T,'R',R,'P',P)
    other_output_keys = ['T_wb','T_dp','Hda','Sda','Vda','Omega']
    outputs = {'psi_w':psi_w,'T':T,'P':P,'R':R}
    for k in other_output_keys:
        outputs[k] = CP.HAPropsSI(k,'T',T,'R',R,'P',P)
    return outputs

def get_supported_input_pairs():
    """ Determine which input pairs are supported """
    good_ones = []
    inputs = generate_values((300, 0.5))
    for k1, k2 in itertools.product(inputs.keys(), inputs.keys()):
        if 'P' in [k1,k2] or k1==k2:
            continue
        args = ('psi_w', k1, inputs[k1], k2, inputs[k2], 'P', inputs['P'])
        try:
            psi_w_new = CP.HAPropsSI(*args)
            if not np.isfinite(psi_w_new):
                raise ValueError('Returned NaN; not ok')
            good_ones.append((k1,k2))
        except BaseException as BE:
            pass
            if 'currently at least one of' in str(BE) or 'cannot provide two inputs' in str(BE):
                pass
            else:
                print(BE)
                good_ones.append((k1,k2))
    return good_ones
supported_pairs = get_supported_input_pairs()

def calculate(inputs):
    """ For a given input, try all possible input pairs """
    errors = []
    for k1, k2 in supported_pairs:
        psi_w_input = inputs['psi_w']
        args = 'psi_w',k1,inputs[k1],k2,inputs[k2],'P',inputs['P']
        try:
            psi_w_new = CP.HAPropsSI(*args)
            if not np.isfinite(psi_w_new):
                raise ValueError('Returned NaN; not ok')
        except BaseException as BE:
            errors.append((str(BE),args, inputs))
    return errors

if __name__ == '__main__':
    import CoolProp
    print(CoolProp.__version__)
    TR = itertools.product(np.linspace(240, 345, 11), np.linspace(0, 1, 11))
    with Pool(processes=2) as pool:
        input_values = pool.map(generate_values, TR)
        errors = pool.map(calculate, input_values)
        for err in itertools.chain.from_iterable(errors):
            print(err)
```