Chemical Engineering (Thermodynamics I) (UCH305)

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Lecture 9

Property Tables

Ideal Gas Law

Outline

- Property tables
- The ideal-gas equation of state

Property tables

- For most substances, the relationships among thermodynamic properties are too complex to be expressed by simple equations.

- In property tables, the results of measurements and calculations are presented in tables in a convenient format.

Steam table- Properties of water are arranged in the steam table as functions of pressure & temperature

- For each substance, the thermodynamic properties are listed in more than one table.

Properties of steam (Saturated water-Temperature table)

Temp., T °C	Sat. Press., P_{sat} kPa	*Specific volume,* m³/kg		*Internal energy,* kJ/kg			*Enthalpy,* kJ/kg			*Entropy,* kJ/kg·K		
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
20	2.339	0.001002	57.762	83.91	2318.4	2402.3	83.91	2453.5	2537.4	0.2965	8.3696	8.6661
25	3.170	0.001003	43.340	104.83	2304.3	2409.1	104.83	2441.7	2546.5	0.3672	8.1895	8.5567
30	4.247	0.001004	32.879	125.73	2290.2	2415.9	125.74	2429.8	2555.6	0.4368	8.0152	8.4520
35	5.629	0.001006	25.205	146.63	2276.0	2422.7	146.64	2417.9	2564.6	0.5051	7.8466	8.3517
40	7.385	0.001008	19.515	167.53	2261.9	2429.4	167.53	2406.0	2573.5	0.5724	7.6832	8.2556
45	9.595	0.001010	15.251	188.43	2247.7	2436.1	188.44	2394.0	2582.4	0.6386	7.5247	8.1633
50	12.35	0.001012	12.026	209.33	2233.4	2442.7	209.34	2382.0	2591.3	0.7038	7.3710	8.0748
55	15.76	0.001015	9.5639	230.24	2219.1	2449.3	230.26	2369.8	2600.1	0.7680	7.2218	7.9898
60	19.95	0.001017	7.6670	251.16	2204.7	2455.9	251.18	2357.7	2608.8	0.8313	7.0769	7.9082
65	25.04	0.001020	6.1935	272.09	2190.3	2462.4	272.12	2345.4	2617.5	0.8937	6.9360	7.8296
70	31.20	0.001023	5.0396	293.04	2175.8	2468.9	293.07	2333.0	2626.1	0.9551	6.7989	7.7540
75	38.60	0.001026	4.1291	313.99	2161.3	2475.3	314.03	2320.6	2634.6	1.0158	6.6655	7.6812
80	47.42	0.001029	3.4053	334.97	2146.6	2481.6	335.02	2308.0	2643.0	1.0756	6.5355	7.6111
85	57.87	0.001032	2.8261	355.96	2131.9	2487.8	356.02	2295.3	2651.4	1.1346	6.4089	7.5435
90	70.18	0.001036	2.3593	376.97	2117.0	2494.0	377.04	2282.5	2659.6	1.1929	6.2853	7.4782
95	84.61	0.001040	1.9808	398.00	2102.0	2500.1	398.09	2269.6	2667.6	1.2504	6.1647	7.4151
100	101.42	0.001043	1.6720	419.06	2087.0	2506.0	419.17	2256.4	2675.6	1.3072	6.0470	7.3542

Steam properties (Saturated water-Pressure table)

Press. P kPa	Sat. Temp., T_{sat} °C	*Specific volume,* m³/kg		*Internal energy,* kJ/kg			*Enthalpy,* kJ/kg			*Entropy,* kJ/kg·K		
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
2.5	21.08	0.001002	54.242	88.42	2315.4	2403.8	88.42	2451.0	2539.4	0.3118	8.3302	8.6421
3.0	24.08	0.001003	45.654	100.98	2306.9	2407.9	100.98	2443.9	2544.8	0.3543	8.2222	8.5765
4.0	28.96	0.001004	34.791	121.39	2293.1	2414.5	121.39	2432.3	2553.7	0.4224	8.0510	8.4734
5.0	32.87	0.001005	28.185	137.75	2282.1	2419.8	137.75	2423.0	2560.7	0.4762	7.9176	8.3938
7.5	40.29	0.001008	19.233	168.74	2261.1	2429.8	168.75	2405.3	2574.0	0.5763	7.6738	8.2501
10	45.81	0.001010	14.670	191.79	2245.4	2437.2	191.81	2392.1	2583.9	0.6492	7.4996	8.1488
15	53.97	0.001014	10.020	225.93	2222.1	2448.0	225.94	2372.3	2598.3	0.7549	7.2522	8.0071
20	60.06	0.001017	7.6481	251.40	2204.6	2456.0	251.42	2357.5	2608.9	0.8320	7.0752	7.9073
25	64.96	0.001020	6.2034	271.93	2190.4	2462.4	271.96	2345.5	2617.5	0.8932	6.9370	7.8302
30	69.09	0.001022	5.2287	289.24	2178.5	2467.7	289.27	2335.3	2624.6	0.9441	6.8234	7.7675
40	75.86	0.001026	3.9933	317.58	2158.8	2476.3	317.62	2318.4	2636.1	1.0261	6.6430	7.6691
50	81.32	0.001030	3.2403	340.49	2142.7	2483.2	340.54	2304.7	2645.2	1.0912	6.5019	7.5931
75	91.76	0.001037	2.2172	384.36	2111.8	2496.1	384.44	2278.0	2662.4	1.2132	6.2426	7.4558
100	99.61	0.001043	1.6941	417.40	2088.2	2505.6	417.51	2257.5	2675.0	1.3028	6.0562	7.3589
125	105.97	0.001048	1.3750	444.23	2068.8	2513.0	444.36	2240.6	2684.9	1.3741	5.9100	7.2841

TABLE A-6 Superheated water

T °C	*v* m^3/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/kg·K
	P = 0.01 MPa (45.81°C)			
Sat.	14.670	2437.2	2583.9	8.1488
50	14.867	2443.3	2592.0	8.1741
100	17.196	2515.5	2687.5	8.4489
150	19.513	2587.9	2783.0	8.6893
200	21.826	2661.4	2879.6	8.9049
250	24.136	2736.1	2977.5	9.1015
300	26.446	2812.3	3076.7	9.2827
400	31.063	2969.3	3280.0	9.6094
500	35.680	3132.9	3489.7	9.8998
600	40.296	3303.3	3706.3	10.1631
700	44.911	3480.8	3929.9	10.4056
800	49.527	3665.4	4160.6	10.6312
900	54.143	3856.9	4398.3	10.8429
1000	58.758	4055.3	4642.8	11.0429
1100	63.373	4260.0	4893.8	11.2326
1200	67.989	4470.9	5150.8	11.4132
1300	72.604	4687.4	5413.4	11.5857

T °C	*v* m^3/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/kg·K
	P = 0.05 MPa (81.32°C)			
Sat.	3.2403	2483.2	2645.2	7.5931
100	3.4187	2511.5	2682.4	7.6953
150	3.8897	2585.7	2780.2	7.9413
200	4.3562	2660.0	2877.8	8.1592
250	4.8206	2735.1	2976.2	8.3568
300	5.2841	2811.6	3075.8	8.5387
400	6.2094	2968.9	3279.3	8.8659
500	7.1338	3132.6	3489.3	9.1566
600	8.0577	3303.1	3706.0	9.4201
700	8.9813	3480.6	3929.7	9.6626
800	9.9047	3665.2	4160.4	9.8883
900	10.828	3856.8	4398.2	10.1000
1000	11.751	4055.2	4642.7	10.3000
1100	12.675	4259.9	4893.7	10.4897
1200	13.598	4470.8	5150.7	10.6704
1300	14.521	4687.3	5413.3	10.8429

Industrial Applications

- Steam used in Turbo-generators for power generations.
- Used in evaporators for concentration of milk, brine solution, black liquor
- Drying applications – paper production, rayon industry, etc.
- Creation of high level vacuum by steam ejectors
- Turbo-pumps, turbo-compressors,

Transport properties of water

Table 11

Physical Properties of Saturated Water [2 and 13]

t, °C	$p \times 10^{-5}$, Pa	ρ, kg/m^3	i', kJ/kg	c_p, kJ/kg·°C	K $\lambda \times 10^2$, W/m·°C	$a \times 10^8$, m^2/s	$\mu \times 10^6$, Pa·s	$\nu \times 10^6$, m^2/s	$\beta \times 10^4$, K^{-1}	$\sigma \times 10^4$, N/m	Pr
0	1.013	999.9	0	4.212	55.1	13.1	1788	1.789	−0.63	756.4	13.67
10	1.013	999.7	42.04	4.191	57.4	13.7	1306	1.306	+0.70	741.6	9.52
20	1.013	998.2	83.91	4.183	59.9	14.3	1004	1.006	1.82	726.9	7.02
30	1.013	995.7	125.7	4.174	61.8	14.9	801.5	0.805	3.21	712.2	5.42
40	1.013	992.2	167.5	4.174	63.5	15.3	653.3	0.659	3.87	696.5	4.31
50	1.013	988.1	209.3	4.174	64.8	15.7	549.4	0.556	4.49	676.9	3.54
60	1.013	983.2	251.1	4.179	65.9	16.0	469.9	0.478	5.11	662.2	3.98
70	1.013	977.8	293	4.187	66.8	16.3	406.1	0.415	5.70	643.5	2.55
80	1.013	971.8	335.0	4.195	67.4	16.6	355.1	0.365	6.32	625.9	2.21
90	1.013	965.3	377.0	4.208	68.0	16.8	314.9	0.326	6.95	607.2	1.95
100	1.013	958.4	419.1	4.220	68.3	16.9	282.5	0.295	7.52	588.6	1.75
110	1.43	951.0	461.4	4.233	68.5	17.0	259.0	0.272	8.08	569.0	1.60
120	1.98	943.1	503.7	4.250	68.6	17.1	237.4	0.252	8.64	548.4	1.47
130	2.70	934.8	546.4	4.266	68.6	17.2	217.8	0.233	9.19	528.8	1.36
140	3.61	926.1	589.1	4.287	68.5	17.2	201.1	0.217	9.72	507.2	1.26
150	4.76	917.0	632.2	4.313	68.4	17.3	186.4	0.203	10.3	486.6	1.17
160	6.18	907.4	675.4	4.346	68.3	17.3	173.6	0.191	10.7	466.0	1.10
170	7.92	897.3	719.3	4.380	67.9	17.3	162.8	0.181	11.3	443.4	1.05
180	10.03	886.9	763.3	4.417	67.4	17.2	153.0	0.173	11.9	422.8	1.00
190	12.55	876.0	807.8	4.459	67.0	17.1	144.2	0.165	12.6	400.2	0.96

Transport properties of air

Physical Properties of Dry Air
($B = 760$ mm Hg $\approx 1.01 \times 10^5$ Pa) [13]

t, °C	ρ, kg/m³	c_p, kJ/kg·°C	$\lambda \times 10^2$, W/m·°C	$a \times 10^6$, m²/s	$\mu \times 10^6$, Pa·s	$\nu \times 10^6$, m²·s	Pr
−50	1.584	1.013	2.04	12.7	14.6	9.23	0.728
−40	1.515	1.013	2.12	13.8	15.2	10.04	0.728
−30	1.453	1.013	2.20	14.9	15.7	10.80	0.723
−20	1.395	1.009	2.28	16.2	16.2	12.79	0.716
−10	1.342	1.009	2.36	17.4	16.7	12.43	0.712
0	1.293	1.005	2.44	18.8	17.2	13.28	0.707
10	1.247	1.005	2.51	20.0	17.6	14.16	0.705
20	1.205	1.005	2.59	21.4	18.1	15.06	0.703
30	1.165	1.005	2.67	22.9	18.6	16.00	0.701
40	1.128	1.005	2.76	24.3	19.1	16.96	0.699
50	1.093	1.005	2.83	25.7	19.6	17.95	0.698
60	1.060	1.005	2.90	26.2	20.1	18.97	0.696
70	1.029	1.009	2.96	28.6	20.6	20.02	0.694
80	1.000	1.009	3.05	30.2	21.1	21.09	0.692
90	0.972	1.009	3.13	31.9	21.5	22.10	0.690
100	0.946	1.009	3.21	33.6	21.9	23.13	0.688
120	0.898	1.009	3.34	36.8	22.8	25.45	0.686
140	0.854	1.013	3.49	40.3	23.7	27.80	0.684
160	0.815	1.017	3.64	43.9	24.5	30.09	0.682
180	0.779	1.022	3.78	47.5	25.3	32.49	0.681
200	0.746	1.026	3.93	51.4	26.0	34.85	0.680
250	0.674	1.038	4.27	61.0	27.4	40.61	0.677
300	0.615	1.047	4.60	71.6	29.7	48.33	0.674
350	0.566	1.059	4.91	81.9	31.4	55.46	0.676
400	0.524	1.068	5.21	93.1	33.0	63.09	0.678
500	0.456	1.093	5.74	115.3	36.2	79.38	0.687
600	0.404	1.114	6.22	138.3	39.1	96.89	0.699
700	0.362	1.135	6.71	163.4	41.8	115.4	0.706
800	0.329	1.156	7.18	188.8	44.3	134.8	0.713
900	0.301	1.172	7.63	216.2	46.7	155.1	0.717
1000	0.277	1.185	8.07	245.9	49.0	177.1	0.719
1100	0.257	1.197	8.50	276.2	51.2	199.3	0.722
1200	0.239	1.210	9.15	316.5	53.5	233.7	0.724

Ideal Gas Law

- Ideal Gas Law:

$$p\,\bar{v} = \bar{R}\,T$$

$$p = pressure,\ kPa$$

$$\bar{v} = molar\ volume,\ \frac{m^3}{kmol}$$

$$\bar{R} = Universal\ gas\ cons\tan t = 8.31451\ \frac{m^3.kPa}{kmol.K}$$

$$0.0831451\ \frac{m^3.bar}{kmol.K}$$

$$T = Absolute\ temperature, K$$

$$p\bar{v} = \bar{R}T$$

or

$$p\frac{V}{n} = \bar{R}T$$

where

$$n = number\ of\ moles$$

$$V = volume, m^3$$

$$pV = n\bar{R}T$$

$$p\,V = n\,\overline{R}\,T$$

or

$$p\,V = n\,M\,\frac{\overline{R}}{M}\,T \quad \left(multiply\ and\ divided\ by\ M, which\ is\ molar\ mass\right)$$

$$p\,V = n\,M\,R\,T \quad \left(R = \frac{\overline{R}}{M} = gas\ cons\,tan\,t\ \ for\ \ particular\ \ gas\right)$$

$$p\,V = m\,R\,T \quad \left(M = \frac{m}{n} \quad or \quad m = n\,M\right)$$

$$pV = mRT$$

$$p\frac{V}{m} = RT$$

$$pv = RT$$

Where

$$v = specific\ volume, \frac{V}{m}, \frac{m^3}{kg}$$

$$p\,V = m\,R\,T$$

$$p = \frac{m}{V}\,R\,T$$

$$p = \rho\,R\,T$$

Where

$$\rho = density, \frac{m}{V}, \frac{kg}{m^3}$$

$$p\;V = m\;R\;T$$

$$p\;\frac{V}{m} = R\;T$$

$$p\;v = R\;T$$

$$p\;\frac{1}{\rho} = R\;T$$

$$p = \rho\;R\;T$$

The Universal Gas Constant - *R values* in alternative Units

atm.cm^3/(mol.K) : 82.0575

atm.ft^3/(lbmol.K) : 1.31443

atm.ft^3/(lbmol.^oR) : 0.73024

atm.l/(mol.K) : 0.08206

bar.cm^3/(mol.K) : 83.14472

bar.l/(mol.K) : 0.08314472

Btu/(lbmol.^oR) : 1.9859

cal/(mol.K) : 1.9859

erg/(mol.K) : 83144720

hp.h/(lbmol.^oR) : 0.0007805

inHg.ft^3/(lbmol.^oR) : 21.85

J/(mol.K) : 8.3144598

kJ/(kmol.K) : 8.3144598

J/(kmol.K) : 8314.472

(kgf/cm^2).l/(mol.K) : 0.084784

kPa.cm^3/(mol.K) : 8314.472

kWh/(lbmol.^oR) : 0.000582

lbf.ft/(lbmol.^oR) : 1545.349

mmHg.ft^3/(lbmol.K) : 999

mmHg.ft^3/(lbmol.^oR) : 555

mmHg.l/(mol.K) : 62.364

Pa.m^3/(mol.K) : 8.314472

psf.ft^3/(lbmol.^oR) : 1545.349

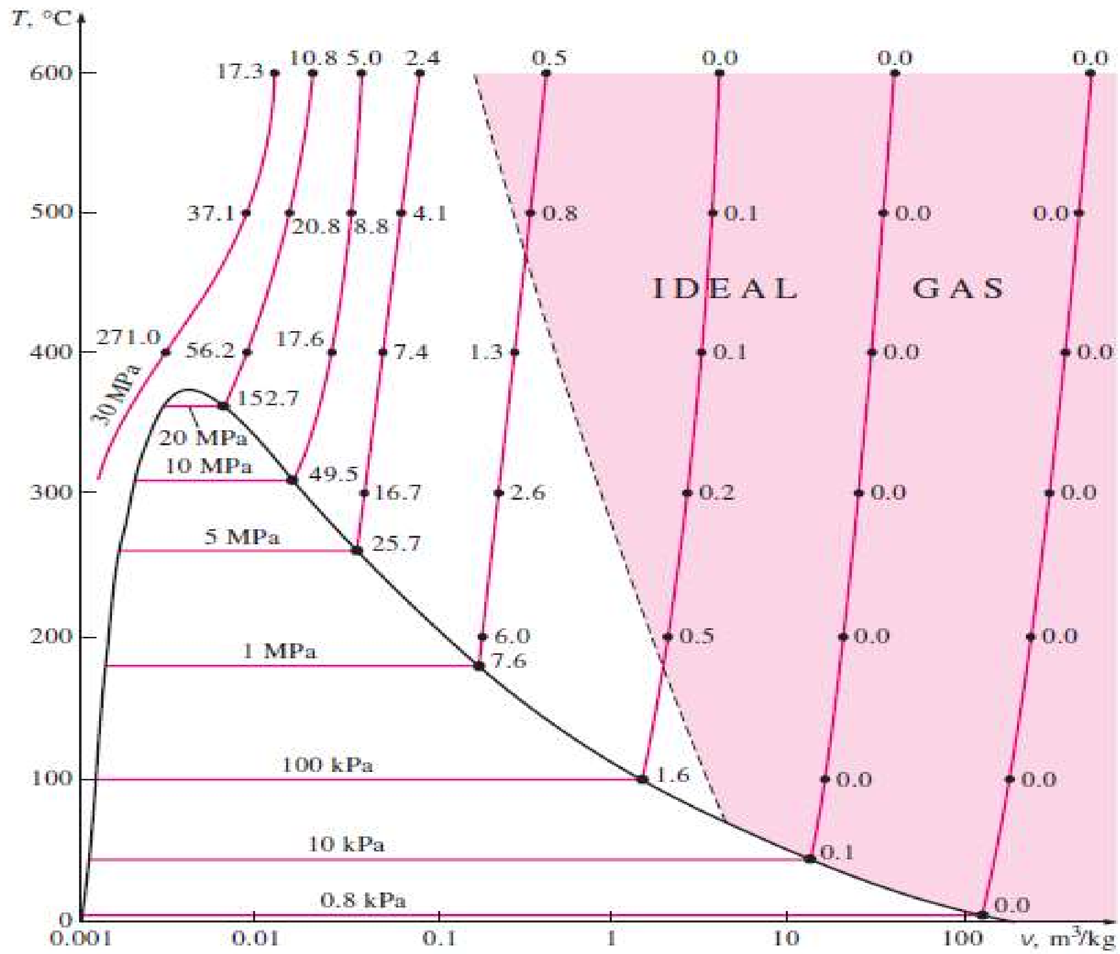
psi.ft^3/(lbmol.^oR) : 10.73

Torr.cm^3/(mol.K) : 62364

Is Water Vapor an Ideal Gas?

- This question cannot be answered with a simple yes or no.

- The error involved in treating water vapor as an ideal gas is calculated and plotted in Fig.



T, °C
600
500
400
300
200
100
0
0.001
0.01
0.1
1
10
100
v, m³/kg
17.3
10.8
5.0
2.4
0.5
0.0
0.0
0.0
37.1
20.8
8.8
4.1
0.8
0.1
0.0
0.0
IDEAL GAS
271.0
56.2
17.6
7.4
1.3
0.1
0.0
0.0
30 MPa
152.7
20 MPa
10 MPa
49.5
16.7
2.6
0.2
0.0
0.0
5 MPa
25.7
6.0
0.5
0.0
0.0
1 MPa
7.6
100 kPa
1.6
0.0
0.0
10 kPa
0.1
0.8 kPa
0.0

- It is clear from this figure that at pressures below 10 kPa, water vapor can be treated as an ideal gas, regardless of its temperature, with negligible error (less than 0.1 percent).

- At higher pressures, however, the ideal gas assumption yields unacceptable errors, particularly in the vicinity of the critical point and the saturated vapor line (over 100 percent).

- Therefore, in air-conditioning applications, the water vapor in the air can be treated as an ideal gas with essentially no error since the pressure of the water vapor is very low.

- For example, the saturation pressure of water vapor in moist air at dry bulb temperature $25^{o}C$ can be $3.130\ kPa$.

- In steam power plant applications, however, the pressures involved are usually very high; therefore, ideal-gas relations should not be used.

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Special Thanks to Professor D. Gangacharyulu.

Thank you for your Patience