Fluid & Gas Properties

FLUID DENSITY

Density is the ratio of mass to volume. In English, units density is expressed in pounds mass/cubic foot (lbm/ft^3). The symbol for density is ρ. Density is usually written as:

$$\rho = \text{lbm/ft}^3$$

The density for a liquid is normally taken from a table. Table 1 lists the densities of various liquids. For steam, the density is typically read from the steam tables for the desired pressure and temperature. For a gas, density is usually calculated using the ideal gas law. The ideal gas law is:

$$\rho = p/RT$$

where p = pressure
R = gas constant
T = temperature

SPECIFIC VOLUME

Specific volume is the reciprocal of density and is the volume occupied by 1 lbm of fluid.

$$v = 1/\rho$$

Table 2 gives the specific volume for saturated steam at various temperatures and pressures.

SPECIFIC GRAVITY

Specific gravity is the ratio of a fluid's density to some reference density. For liquids, the reference density is the density of pure water. Strictly speaking, specific gravity of a liquid cannot be given without specifying the reference temperature at which the water's density was evaluated. The density of water in English units is normally referenced at 32°F and is 62.43 lbm/ft^3. Using this as the reference density, specific gravity is given as:

$$\text{S.G.} = \frac{\text{density}}{62.43\text{lbm/ft}^3}$$

RELATIVE DENSITY

Relative density is the ratio of the density of one substance to that of another, both at the same temperature. The use of specific gravity to describe this quantity is discouraged, partially due to the fact there is no stipulation that the temperatures be equal in specific gravity measurements.

For gasses, the relative density is generally the ratio of the density of the gas to that of air, again both at the same temperature, and also at the same pressure and dryness.

Relative densities of petroleum products and aqueous acid solutions can be found using a device called a hydrometer. In addition to the hydrometer scale that references water, there are two basic hydrometer scales, the Baume scale and the API (American Petroleum Industry Scale). The Baume scale was widely used in the past but the API scale is now recommended for use with all liquids.

The API scale can be used with all liquids:

$$\text{Relative Density} = \frac{141.5}{131.5+°\text{API}}$$

Table 3 lists the relative densities corresponding to the API scale.

For liquids lighter than water, their specific gravity can be found from the Baume hydrometer reading using this equation:

$$\text{Relative Density} = \frac{140.0}{130.0+°\text{Baume}}$$

For liquids heavier than water, their specific gravity can be found from the Baume hydrometer reading using this equation:

$$\text{Relative Density} = \frac{145.0}{145.0-°\text{Baume}}$$

Relative densities can also be given for gases. The reference density is that of air at specified temperature and pressure. Since both the gas and air are evaluated at the same pressure and temperature, the relative density is the inverse of the ratio of the gas constants.

TABLE 1 Density of Liquids

Liquid	Temperature °F	Density lbm/ft^3	Specific Gravity redl H_2O @60°F
Acetaldehyde	64	48.9	0.784
Acetone	60	49.4	0.792
Acetic Anhydride	68	67.5	1.083
Acetic Acid (conc)	68	65.5	1.050
Ammonia	10	40.9	0.656
Aniline	68	63.8	1.023
Benzene	32	56.1	0.899
Benzoic Acid	59	79.0	1.267
Brine, 10% CaCl	32	68.1	1.091
Brine, 10% NaCl	32	67.2	1.078
Butyric Acid (conc)	68	60.2	0.965
Carbon Disulfide	32	80.6	1.292
Carbon Tetrachloride	68	99.6	1.597
Chlorobenzene	68	69.1	1.108
Chloroform	68	92.9	1.489
Cresol, Meta	68	64.5	1.035
Diphenyl	163	61.9	0.993
Distillate	60	53.0	0.850
Fuel Oil #6 (min)	60	61.9	0.993
Furfural	68	72.3	1.160
Gasoline	60	46.8	0.751
Gasoline (natural)	60	42.4	0.680
Glycerin	112	78.6	1.261
Heptane	68	42.7	0.685
Hydrochloric Acid (42.5%)	64	92.3	1.400
Hydrocyanic Acid	64	43.5	0.697
Kerosene	60	50.8	0.815
Mercury	20	849.7	13.623
	40	848.0	13.596
	60	846.3	13.568
	80	844.6	13.541
	100	842.9	13.514
Methylene Chloride	68	83.4	1.337
Milk	--	64.2 - 64.6	--
Nitric Acid (conc)	64	93.7	1.502
Olive Oil	59	57.3	0.919
Ortho-phosphoric Acid	65	114.4	1.834
Pentane	59	38.9	0.624
Phenol	77	66.8	1.072
Toluene	68	54.1	0.867
Xylene	68	55.0	0.882

Reference - Fluid & Gas Properties

TABLE 2 Properties of Saturated Steam

Pressure PSIA	Temp °F	Sp. Vol. ft³/lbm	Pressure PSIA	Temp °F	Sp. Vol. ft³/lbm	Pressure PSIA	Temp °F	Sp. Vol. ft³/lbm
0.50	79.58	641.4	80.0	312.03	5.472	250.0	400.95	1.8438
1.0	101.74	333.6	85.0	316.25	5.168	275.0	409.43	1.6804
2.0	126.08	173.73	90.0	320.27	4.896	300.0	417.33	1.5433
3.0	141.48	118.71	95.0	324.12	4.652	350.0	431.72	1.3260
4.0	152.97	90.63	100.0	327.81	4.432	400.0	444.59	1.1613
5.0	162.24	73.52	105.0	331.36	4.232	450.0	456.28	1.0320
10.0	193.21	38.42	110.0	334.77	4.049	500.0	467.01	0.9278
14.7	212.00	26.80	115.0	338.07	3.882	550.0	476.93	0.8422
15.0	213.03	26.29	120.0	341.25	3.728	600.0	486.21	0.7698
20.0	227.96	20.089	125.0	344.33	3.587	650.0	494.90	0.7085
25.0	240.07	16.303	130.0	345.32	3.455	700.0	503.10	0.6554
30.0	250.33	13.746	135.0	350.21	3.333	750.0	510.85	0.6094
35.0	259.28	11.898	140.0	353.02	3.220	800.0	518.23	0.5687
40.0	267.25	10.498	145.0	355.76	3.114	850.0	525.26	0.5328
45.0	274.44	9.401	150.0	358.42	3.015	900.0	531.98	0.5006
50.0	281.01	8.515	160.0	363.53	2.834	950.0	538.42	0.4718
55.0	287.07	7.787	170.0	368.41	2.675	1000	544.61	0.4456
60.0	292.71	7.175	180.0	373.06	2.532	1250	572.42	0.3450
65.0	297.97	6.665	190.0	377.51	2.404	1500	596.23	0.2765
70.0	302.92	6.206	200.0	381.79	2.288	1750	617.09	0.2267
75.0	307.60	5.816	225.0	391.79	2.042	2000	635.82	0.1878

TABLE 3 Relative Density at 60°/60°F Corresponding to the API Scale

Degree API	Relative Density	Pound US Gal.	Degree API	Relative Density	Pound US Gal.	Degree API	Relative Density	Pound US Gal.
10	1.0000	8.328	41	0.8203	6.830	71	0.6988	5.817
11	0.9930	8.270	42	0.8155	6.790	72	0.6953	5.788
12	0.9861	8.212	43	0.8109	6.752	73	0.6919	5.759
13	0.9792	8.155	44	0.8063	6.713	74	0.6886	5.731
14	0.9725	8.099	45	0.8017	6.675	75	0.6852	5.703
15	0.9659	8.044	46	0.7972	6.637	76	0.6819	5.676
16	0.9593	7.989	47	0.7927	6.600	77	0.6787	5.649
17	0.9529	7.935	48	0.7883	6.563	78	0.6754	5.622
18	0.9465	7.882	49	0.7839	6.526	79	0.6722	5.595
19	0.9402	7.830	50	0.7796	6.490	80	0.6690	5.568
20	0.9340	7.778	51	0.7753	6.455	81	0.6659	5.542
21	0.9279	7.727	52	0.7711	6.420	82	0.6628	5.516
22	0.9218	7.676	53	0.7669	6.385	83	0.6597	5.491
23	0.9159	7.627	54	0.7628	6.350	84	0.6566	5.465
24	0.9100	7.578	55	0.7587	6.316	85	0.6537	5.440
25	0.9042	7.529	56	0.7547	6.283	86	0.6506	5.415
26	0.8984	7.481	57	0.7507	6.249	87	0.6476	5.390
27	0.8927	7.434	58	0.7467	6.216	88	0.6446	5.365
28	0.8871	7.387	59	0.7428	6.184	89	0.6417	5.341
29	0.8816	7.341	60	0.7389	6.151	90	0.6388	5.316
30	0.8762	7.296	61	0.7351	6.119	91	0.6360	5.293
31	0.8708	7.251	62	0.7313	6.087	92	0.6331	5.269
32	0.8654	7.206	63	0.7275	6.056	93	0.6303	5.246
33	0.8602	7.163	64	0.7238	6.025	94	0.6275	5.222
34	0.8550	7.119	65	0.7201	5.994	95	0.6247	5.199
35	0.8498	7.076	66	0.7165	5.964	96	0.6220	5.176
36	0.8448	7.034	67	0.7128	5.934	97	0.6193	5.154
37	0.8398	6.993	68	0.7093	5.904	98	0.6160	5.131
38	0.8348	6.951	69	0.7057	5.874	99	0.6139	5.109
39	0.8299	6.910	70	0.7022	5.845	100	0.6112	5.086
40	0.8251	0.870						

ACFM vs. SCFM

It is often desirable to express a gas flow in terms of a "standard" volumetric flowrate. One of the most common forms encountered is standard cubic feet per minute (scfm). To convert an actual flowrate reading, here referred to as actual cubic feet per minute (acfm), it is necessary to multiply the actual flowrate by the ratio of the standard condition's specific volume over the actual condition's specific volume.

$$Q_S = Q_A [v_S / v_A]$$

where: Q_S = flowrate in scfm

Q_A = flowrate in acfm

v_S = standard conditions specific volume

v_A = actual conditions specific volume

The ratio v_S / v_A can be written as:

$$[T_S P_A / P_S T_A]$$

IDEAL GAS BEHAVIOR

A gas can be considered ideal if it exhibits ideal gas behavior. Typically, gases at low pressures and at temperatures much higher than their critical temperatures can be treated as ideal gases. When the volume occupied by the gas molecules is negligible in comparison to the total volume, it is acceptable to treat the gas as an ideal gas. The benefit of treating gases as ideal is that it greatly simplifies the math required to evaluate their behavior.

There are two basic laws that define the behavior of ideal gases; they are Boyle's and Charle's Law. Boyle's law states that the volume and pressure of an ideal gas vary inversely when the temperature is held constant and is written as:

$$p_1V_1 = p_2V_2$$

The second law is Charle's law that states when pressure is held constant, volume and temperature vary proportionally. Charle's law is written:

$$\frac{T_1 = T_2}{V_1 \quad T_2}$$

The ideal gas law relates the pressure, temperature, and volume to the amount of gas present. The ideal gas law states that equal volumes of different gases at the same temperature and pressure contain the same number of molecules. The ideal gas law is written:

$$pV = nR^*T$$

R* is known as the universal gas constant. It is universal because the same number can be used with any gas. Due to the different units that can be used for pressure, temperature, and volume, there are different values of R*. Table 4 lists values for R*.

The ideal gas law can be used with more than 1 mole of gas. If there are n moles, the equation is written as:

$$n = m/M$$

TABLE 4 Values of Universal Gas Constant

1545.33	ft-lbf/pmole-°R
0.08206	atm-liter/gmole-°K
1.986	BTU/pmole-°R
1.986	cal/gmole-°K
8.314	joule/gmole-°K
0.730	atm-ft3/pmole-°R

The ideal gas law can be rewritten taking into account the molecular weight of the specific gas. The specific gas constant is unique for each gas.

$$pV = mR^*t/M$$

$$pV = mT(R^*/M)$$

$$pV = mRT$$

Table 5 lists the properties of common gases.

Since density is the reciprocal of specific volume, the ideal gas law can be used to determine the density of an ideal gas. If m=1, then the ideal gas law can be rewritten as:

$$p = \frac{1RT}{v}$$

$$p = RT$$

$$\rho = \frac{p}{RT}$$

PROPERTIES OF REAL GASES

Unfortunately, it is not always possible to achieve acceptable results by using the ideal gas law. It is very common for gases at low temperatures and/or high pressures to exhibit real gas behavior.

When the spacing between the gas molecules is small, they tend to attract each other. These attractive forces are called Van der Waals forces. Van der Waal's equation of state can be used to describe the behavior of real gases. Van der Waal's equation of state is written as:

$$(p+\frac{a}{V^2})(V-b) = nR^*T$$

For an ideal gas, a and b are zero and Van der Waal's equation reduces to the familiar ideal gas law.

Since real gas molecules tend to attract each other, the actual pressure exerted by a real gas is less than that predicted by the ideal gas law. The reduction in pressure is corrected for in the Van der Waal equation by the term (a/V2). The constant b is dependent on the volume occupied by the gas molecules in the dense state. Table 6 gives the values for a and b of common gases. The Van der Waal equation is typically used only when the gas is below critical pressure.

Reference - *Fluid & Gas Properties*

TABLE 5 Properties of Common Gases

Gas	Symbol	MW	R	Density	k
Acetylene	C_2H_2	26.0	59.4	0.07323	1.30
Air	---	29.0	53.3	0.08071	1.40
Ammonia	NH_3	17.0	91.0	0.04813	1.32
Argon	A	39.9	38.7	0.11135	1.67
Carbon Dioxide	CO_2	44.0	35.1	0.12341	1.28
Carbon Monoxide	CO	28.0	55.2	0.07806	1.40
Chlorine	Cl_2	70.9	21.8	0.2006	1.33
Ethane	C_2H_6	30.07	51.3	0.08469	1.18
Ethylene	C_2H_4	28.0	55.1	0.07868	1.22
Freon (R-12)	CCl_2F_2	120.9	12.6	---	1.13
Helium	He	4.0	386.3	0.01114	1.66
Hydrogen	H_2	2.0	766.8	0.00561	1.41
Isobutane	C_4H_{10}	58.12	26.6	---	1.09
Krypton	Kr	82.9	18.6	0.2315	1.67
Methane	CH_4	16.0	96.4	0.04475	1.32
Neon	Ne	20.18	76.4	0.05621	1.64
Nitrogen	N_2	28.0	55.2	0.07807	1.40
Oxygen	O_2	32.0	48.3	0.08921	1.40
Propane	C_3H_8	44.09	35.0	0.1254	1.12
Steam**	H_2O	18.0	85.8	---	1.28
Sulfur Dioxide	SO_2	64.1	24.0	0.1827	1.26
Xenon	Xe	130.2	11.9	---	1.67

** *Values for steam are approximate and may be used only for low pressures and high temperatures. R is in ft-lbf/lbm-°R, Density is in lbm/ft³ at 32°F and 14.7 PSIA.*

TABLE 6 Values of a and b for Common Gases

	a(atm-ft⁶/pmole)	b(ft³/pmole)
Air	345.2	0.585
CO_2	926	0.686
H_2	62.8	0.427
O_2	348	0.506
Steam	1400	0.488

There is another correction factor that is applied to real gases. This factor is known as the compressibility factor, and is sometimes used for correction of gas flows through orifices. The compressibility factor is denoted by Z, and is dependent on pressure, temperature, and the type of gas. The modified ideal gas law is:

$$pV = ZRT$$

Correction factors for gases can be plotted against pressure and temperature. By using the principle of corresponding states, it is possible to create one graph that covers multiple gases. The principle of corresponding states says that all gases behave alike whenever they have the same reduced variables. The reduced variables that the law refers to are the ratios of pressure, temperature, and volume to their critical values. Table 7 gives critical properties for selected gases.

$$P_r = P/P_c$$

$$T_r = T/T_c$$

$$V_r = v/v_c$$

TABLE 7 Approximate Critical Properties

gas	T_c(°R)	P_C (psia)
Air	235.8	547.0
Ammonia	730.1	1639.0
Argon	272.2	705.0
Carbon Dioxide	547.8	1071.0
Carbon Monoxide	242.2	508.2
Chlorine	751.0	1116.0
Ethane	549.8	717.0
Ethylene	509.5	745.0
Helium	10.0	33.8
Hydrogen	60.5	188.0
Mercury	2109.0	2646.0
Methane	343.9	673.3
Neon	79.0	377.8
Nitrogen	227.2	492.5
Oxygen	278.1	730.9
Propane	666.3	617.0
Sulfur Dioxide	775.0	1141.0
Water Vapor	1165.4	3206.0
Xenon	521.9	855.3

Figures 1 and 2 are graphs of compressibility factors.

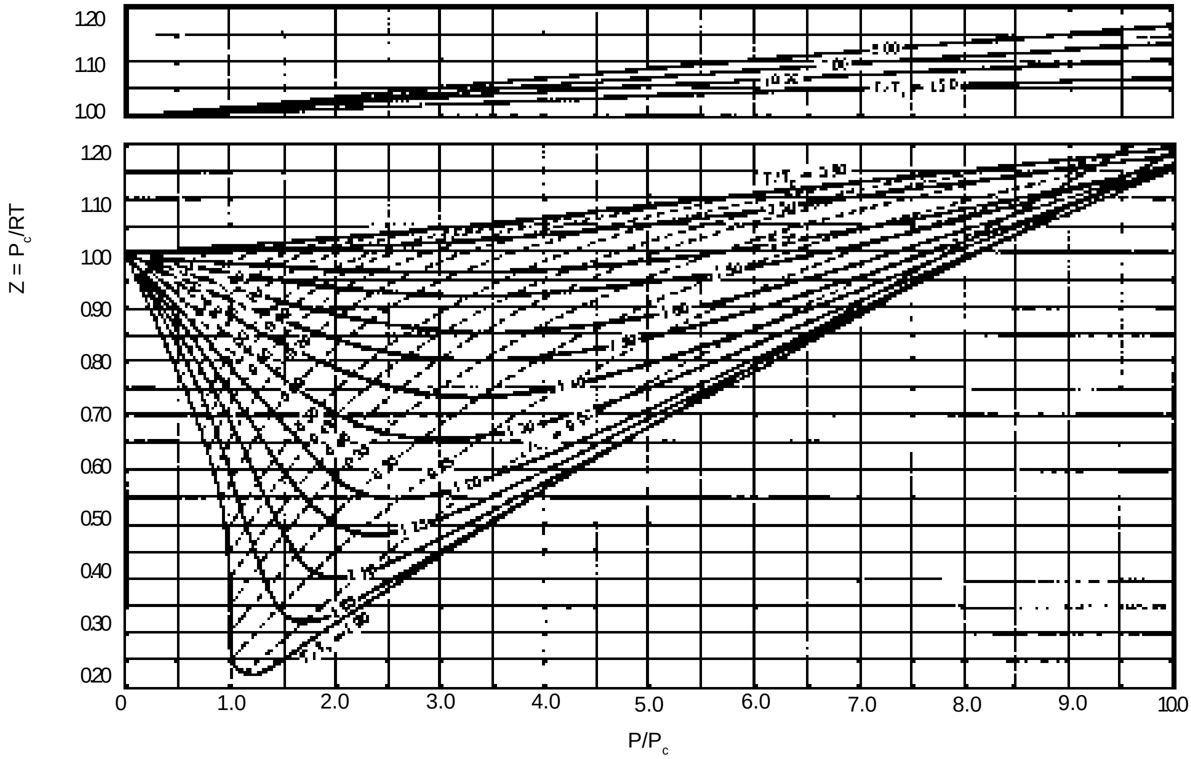

FIGURE 1 Compressibility Factors for Low Pressure as presented by Professor E. Obert and L. Nelson in "Generalized P-V-T Properties of Gases," ASME Transactiona, 76, 1057 (1954)

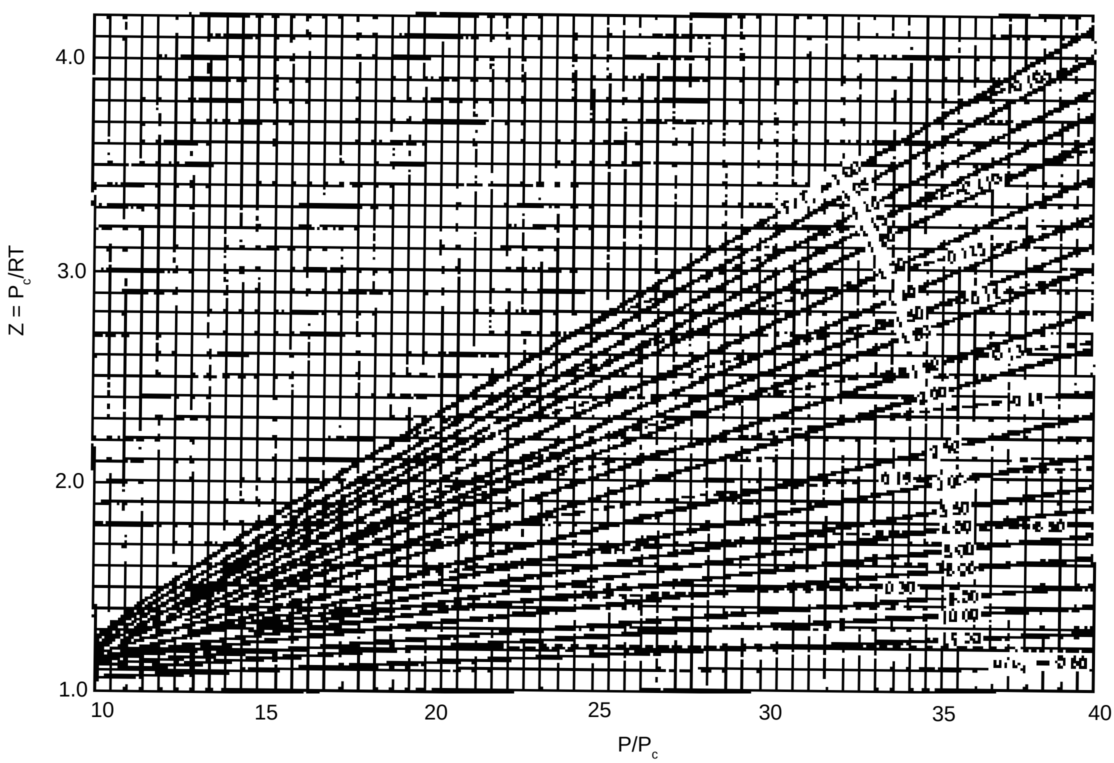

FIGURE 2 Compressibility Factors for High Pressure

VISCOSITY

The viscosity of a liquid is a measure of its resistance to flow. Liquids can be categorized by their viscosity properties. One of the most common liquid categories is Newtonian liquids.

Viscosity is measured using two parallel plates and a layer of fluid. The plates are separated from each other by a layer of fluid with a thickness of y. One plate is fixed and the other one is maintained at a constant velocity by a constant force F.

It has been shown that for Newtonian fluids, the force required to maintain the velocity is proportional to the velocity and inversely proportional to the separation of the plates.

$$\frac{F}{A} = \frac{dv}{dy}$$

The constant of proportionality is the absolute viscosity. The quantity F/A is the shear stress in the fluid. The equation can be written as:

$$t = u(dv/dy)\ \rho$$

Kinematic viscosity is also used commonly and is a combination of absolute viscosity and the density of the fluid.

$$v = ug/\rho$$

Tables 8 and 9 give conversion factors for the most commonly encountered viscosity units.

TABLE 8 Equivalents of Absolute Viscosity

Absolute Viscosity	Centipoise	Poise	Pound / Ft Sec
Centipoise	1	0.01	0.000672
Poise	100	1	0.0672
Pound / Ft Sec	1487	14.87	1

TABLE 9 Equivalents of Kinematic Viscosity

Kinematic Viscosity	Centistoke	Stoke	Ft^2 / Sec
Centistoke	1	0.01	0.00001076
Stoke	100	1	0.001076
Ft^2 / Sec	92,900	929	1

Table 10 lists the viscosity of common liquids and Table 11 lists the viscosity of common gases.

TABLE 10 Viscosity of Common Liquids

Temperature °F	Viscosity Centipoise
Acetic Acid	
59	1.31
64	1.30
77	1.155
86	1.04
106	1.00
212	0.43
Acetic Anhydride	
32	1.24
59	0.971
64	0.90
86	0.783
212	0.490
Acetone	
14	0.450
32	0.399
59	0.337
77	0.316
Ammonia	
-92	0.475
-58	0.317
-40	0.276
-28	0.255
Benzene	
32	0.912
50	0.758
68	0.652
86	0.564
104	0.503
122	0.542
Carbon Tetrachloride	
32	1.329
59	1.038
68	0.969
86	0.843
104	0.739
140	0.585
Chlorine Liquid	
-40	0.505
-20	0.462
20	0.400
60	0.350
100	0.313
Ethylbenzene	
63	0.691
Ethylene Glycol	
68	19.9
104	9.13
140	4.95
176	3.02

Temperature °F	Viscosity Centipoise
Ethylene Oxide	
-57	0.577
-37	0.488
-5.8	0.394
32	0.320
Fluorbenzene	
68	0.598
140	0.389
212	0.275
Fuel Oil, #2	
70	3.0 - 7.4
100	2.11 - 4.28
Fuel Oil, #6	
122	97.4 - 660
160	37.5 - 172
Gasoline	
60	0.46 - 0.88
100	0.40 - 0.71
Glycerin	
32	12,110
43	6,260
59	2,330
68	1,490
77	954
86	629
Heptane	
32	0.524
63	0.461
68	0.409
77	0.386
104	0.341
Hexane	
32	0.401
68	0.326
77	0.386
104	0.341
Hyrdochloric Acid, 31.5%	
0	3.4
20	2.9
40	2.5
60	2.0
80	1.8
100	1.6
140	1.2
Iodine Liquid	
241	2.27
Isoheptane	
32	0.481
68	0.384
104	0.315

Temperature °F	Viscosity Centipoise
Isohexane	
32	0.376
68	0.306
104	0.254
Isopentane	
32	0.273
68	0.223
Kerosene	
68	2.69
100	2.0
Methyl Alcohol	
-48	1.98
32	0.82
59	0.623
68	0.597
77	0.546
86	0.510
Methyl Chloride	
0	0.25
20	0.23
40	0.21
60	0.19
100	0.16
Naphthalene	
176	0.967
212	0.776
Nitric Acid	
32	2.275
Nitrobenzene	
37	2.91
42	2.71
50	2.48
68	2.03
Nitromethane	
32	0.853
77	0.620
n-Octane	
32	0.706
68	0.240
104	0.433
Pentane	
32	0.289
68	0.524
Phenol	
65	12.7
122	3.49
158	2.03
194	1.26

(continued)

TABLE 10 Viscosity of Common Liquids (continued)

Temperature °F	Viscosity Centipoise	Temperature °F	Viscosity Centipoise	Temperature °F	Viscosity Centipoise
Phosphorus Liquid		Sodium Liquid		Sulfuric Acid	
71	2.34	0	2.4	32	48.4
88	2.01	26	1.3	59	32.8
110	1.73	40	1.2	68	25.4
123	1.60	60	1.1	86	15.7
140	1.45	100	1.0	104	11.5
158	1.32	140	0.85	122	8.82
Sodium Hydroxide		Sulfur (gas free)		140	7.22
70	100	253	10.9	Turpentine	
100	40	276	8.7	60	2.11
120	25	301	7.1	100	2.0
140	15	314	7.2	Water	
160	9.5	317	7.6	60	1.13
200	3.7	319	14.5	130	0.55
220	2.4	Sulfur Dioxide			
250	1.4	-28	0.5508		
		13	0.4285		
		32	0.3936		

TABLE 11 Viscosity of Common Gases

Temperature °F	Viscosity Centipoise
Acetylene	
32	0.00935
Air	
32	0.0171
104	0.0190
444	0.0264
633	0.0305
674	0.0312
768	0.0341
Ammonia	
32	0.0092
68	0.0098
212	0.0128
302	0.0146
482	0.0181
Argon	
32	0.0210
68	0.0222
212	0.0269
392	0.0322
Benzene	
0	0.0065
40	0.0070
70	0.0075
100	0.0080
200	0.0091
Butene	
0	0.0075
40	0.0080
70	0.0085
100	0.0090
200	0.0104
Butylene	
66	0.0074
212	0.0095
Carbon Dioxide	
-144	0.0090
-76	0.0106
32	0.0139
68	0.0148
86	0.0153
Carbon Monoxide	
32	0.0166
59	0.0172
260.8	0.0218
Chlorine	
122	0.0147
212	0.0168
302	0.0187
392	0.0208
Ethane	
32	0.0085
63	0.0090
Ethylene	
32	0.0091
68	0.0101
122	0.0110
212	0.0126
Helium	
32	0.0186
68	0.0194
Hydrogen	
-172	0.0057
-143.5	0.0062
-25	0.0077
32	0.0084
69	0.0088
264	0.0108
Hydrogen Chloride	
54.4	0.0139
61.8	0.0141
212	0.0182
Hydrogen Sulfide	
32	0.0117
62.6	0.0124
212	0.0159
Methane	
32	0.0102
68	0.0109
212	0.0133
Nitrogen	
-6.7	0.0156
51.6	0.0171
81	0.0178
261	0.0219
440	0.0256
Oxygen	
32	0.0189
67	0.0202
262	0.0257
440	0.0302
n-Pentane	
77	0.0068
212	0.0084
Propane	
64.2	0.0079
213	0.0101
Propylene	
62	0.0083
122	0.0093
Sulfur Dioxide	
32	0.0116
64.4	0.0124
68.9	0.0125
213	0.0161

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Reference