Refrigeration Engineer Quick Reference

Thermodynamic Laws

Zeroth Law: When two systems are in thermal equilibrium with a third system, they must be in thermal equilibrium with each other.

First Law (closed system): $Q = m\Delta u + W/J$
Heat entering a system can either increase temperature (internal energy) or be used to perform work on the surroundings. It is the law of energy conservation, i.e., energy cannot be created or destroyed.

Second Law (isolated system): $m\Delta s_{total} \geq 0$
The entropy change of any system and its surroundings, considered together, is positive, and approaches zero for any process that approaches reversibility. It is considered the fundamental law of natural science.

The two classical statements of the Second Law:

Clausius statement: It is impossible to construct a device that operates in a cycle and produces no effect other than the transfer of heat from a cooler body to a hotter body.

Kelvin-Plank statement: It is impossible to construct a device that operates in a cycle and produces no effect other than the raising of a weight and the exchange of heat with a single reservoir.

Third Law: It is impossible to cool a body down to absolute zero.

Thermodynamic Laws (simplified)

First Law: You can't win, you can only break even.

Second Law: You can only break even at absolute zero.

Third Law: You can never reach absolute zero.

Thermodynamic Equations

Ideal Gas Law: $pV = nRT = NkT;\quad V = mv;\quad n = m/M;\quad k = R/N_A$

Helmholtz Function: $f = u - Ts$

Gibbs Function: $g = h - Ts$

Equation of State: $p = -J\left(\frac{\partial f}{\partial v}\right)_T$

The four thermodynamic potentials:

	$\xrightarrow{-Ts}$	
$\downarrow +pv/J$	u	f
	h	g

Enthalpy:

$$h = u + pv/J = \int\left[c_v + \frac{v}{J}\left(\frac{\partial p}{\partial T}\right)_v\right]dT + \frac{1}{J}\int\left[v\left(\frac{\partial p}{\partial v}\right)_T + T\left(\frac{\partial p}{\partial T}\right)_v\right]dv$$

Entropy: $s = -\left(\frac{\partial f}{\partial T}\right)_v = -\left(\frac{\partial g}{\partial T}\right)_p = \int\frac{c_v dT}{T} + \frac{1}{J}\int\left(\frac{\partial p}{\partial T}\right)_v dv$

Isochoric Specific Heat: $c_v = \left(\frac{\partial u}{\partial T}\right)_v = T\left(\frac{\partial s}{\partial T}\right)_v = c_v^0 + \frac{1}{J}\int_\infty^v T\left(\frac{\partial^2 p}{\partial T^2}\right)_v dv$

Isobaric Specific Heat: $c_p = \left(\frac{\partial h}{\partial T}\right)_p = T\left(\frac{\partial s}{\partial T}\right)_p = c_v - \frac{T\left(\frac{\partial p}{\partial T}\right)_v^2}{J\left(\frac{\partial p}{\partial v}\right)_T}$

Specific Heat Ratio: $\gamma = c_p/c_v = \kappa/\kappa_s$

Velocity of Sound:

$$a = v\sqrt{Jg_c\gamma\left(\frac{\partial^2 f}{\partial v^2}\right)_T} = v\sqrt{-g_c\gamma\left(\frac{\partial p}{\partial v}\right)_T} = v\sqrt{g_c\left[\frac{T\left(\frac{\partial p}{\partial T}\right)_v^2}{Jc_v} - \left(\frac{\partial p}{\partial v}\right)_T\right]}$$

Nomenclature		I-P	S-I
a	velocity of sound	ft/sec	m/sec
c_p	isobaric specific heat	Btu/lb$_m$-°R	kJ/kg-°K
c_v	isochoric specific heat	Btu/lb$_m$-°R	kJ/kg-°K
f	Helmholtz function	Btu/lb$_m$	kJ/kg
g	Gibbs function	Btu/lb$_m$	kJ/kg
g_c	gravitational conversion factor	32.174 lb$_m$-ft/lb$_f$-sec^2	1.0
h	enthalpy	Btu/lb$_m$	kJ/kg
J	Joule's constant	778.16926 ft-lb$_f$/Btu	1.0
m	mass	lb$_m$	kg
M	molecular weight	---	---
N	no. of molecules	---	---
n	no. of moles	lb mol	kg mol
p	pressure	lb$_f$/ft^2	kPa
Q	heat	Btu	kJ
s	entropy	Btu/lb$_m$-°R	kJ/kg-°K
T	temperature	°R	°K
u	internal energy	Btu/lb$_m$	kJ/kg
v	specific volume	ft^3/lb$_m$	m^3/kg
V	volume	ft^3	m^3
W	work	ft-lb$_f$	kJ
κ	isothermal compressibility	ft^2/lb$_f$	(kPa)$^{-1}$
κ_s	adiabatic compressibility	ft^2/lb$_f$	(kPa)$^{-1}$
γ	specific heat ratio	---	---

Superscript: 0 = heat capacity at zero pressure

(Physical Constants on reverse side.)

Carrying Capacity of Refrigeration Lines - Tons of Refrigeration

R-22

Line Size	Suction Lines								Liquid Lines				Discharge Lines	
Type L Copper OD (Inches)	Velocity = 1500 fpm				Δt = 1°F Δp = 0.39 psi	Δp = 0.57 psi	Δp = 0.81 psi	Δp = 1.1 psi	Velocity = 150 fpm		Δt = 1°F, Δp = 1.9 psi		Δt = 1°F, Δp = 3.0 psi	
	Suction Temperature (°F) -40	-20	0	20	Suction Temperature (°F) -40	-20	0	20	Suction Temperature (°F) -20	20	-20	20	Suction Temperature (°F) -20	20
3/8	0.09	0.14	0.22	0.33	0.02	0.04	0.06	0.09	2.27	2.40	0.94	0.99	0.39	0.42
1/2	0.17	0.27	0.43	0.64	0.06	0.10	0.15	0.23	4.35	4.58	2.25	2.37	0.92	1.00
5/8	0.27	0.44	0.68	1.03	0.11	0.18	0.29	0.43	6.98	7.36	4.25	4.48	1.73	1.88
7/8	0.56	0.91	1.42	2.13	0.30	0.49	0.76	1.13	14.5	15.3	11.3	11.9	4.53	4.93
1-1/8	0.95	1.55	2.42	3.63	0.61	0.99	1.54	2.30	24.7	26.0	23.1	24.3	9.16	9.96
1-3/8	1.45	2.36	3.69	5.53	1.06	1.74	2.70	4.02	37.6	39.6	40.4	42.6	15.9	17.3
1-5/8	2.05	3.35	5.22	7.83	1.69	2.76	4.28	6.37	53.3	56.1	64.1	67.6	25.2	27.4
2-1/8	3.57	5.82	9.07	13.6	3.54	5.76	8.92	13.2	92.6	97.6	134	141	52.0	56.5
2-5/8	5.51	8.98	14.0	21.0	6.29	10.2	15.8	23.4	143	150	237	250	91.7	99.7
3-1/8	7.87	12.8	20.0	30.0	10.1	16.4	25.3	37.5	204	215	379	400	146	159
3-5/8	10.6	17.3	27.0	40.6	15.0	24.4	37.7	55.7	276	291	565	595	217	235
4-1/8	13.8	22.5	35.1	52.7	21.3	34.5	53.2	78.7	359	378	798	841	305	331
5-1/8	21.6	35.1	54.7	82.2	38.3	61.9	95.4	141	559	589	1430	1510	544	590
6-1/8	31.0	50.5	78.7	118	61.7	99.8	154	227	803	846	2310	2430	872	947

R-134a

Line Size	Suction Lines						Liquid Lines				Discharge Lines	
Type L Copper OD (Inches)	Velocity = 1500 fpm			Δt = 1°F Δp = 0.33 psi	Δp = 0.49 psi	Δp = 0.70 psi	Velocity = 150 fpm		Δt = 1°F, Δp = 1.3 psi		Δt = 1°F, Δp = 2.2 psi	
	Suction Temperature (°F) -20	0	20	Suction Temperature (°F) -20	0	20	Suction Temperature (°F) -20	20	-20	20	Suction Temperature (°F) -20	20
3/8	0.08	0.13	0.21	0.02	0.03	0.06	2.11	2.29	0.68	0.73	0.28	0.30
1/2	0.15	0.25	0.40	0.05	0.08	0.13	4.03	4.37	1.63	1.77	0.66	0.72
5/8	0.24	0.40	0.64	0.09	0.16	0.25	6.47	7.02	3.10	3.36	1.23	1.35
7/8	0.50	0.84	1.33	0.25	0.42	0.67	13.4	14.6	8.27	8.97	3.23	3.56
1-1/8	0.86	1.43	2.27	0.51	0.86	1.36	22.9	24.8	16.9	18.3	6.54	7.20
1-3/8	1.31	2.17	3.46	0.90	1.50	2.38	34.8	37.8	29.7	32.2	11.4	12.5
1-5/8	1.85	3.08	4.90	1.43	2.38	3.78	49.3	53.5	47.1	51.1	18.0	19.8
2-1/8	3.21	5.35	8.53	2.99	4.98	7.88	85.8	93.1	98.4	107	37.2	40.9
2-5/8	4.96	8.25	13.1	5.31	8.84	14.0	132	144	175	190	65.6	72.2
3-1/8	7.07	11.8	18.8	8.53	14.2	22.4	189	205	280	304	105	115
3-5/8	9.57	15.9	25.4	12.7	21.1	33.3	255	277	418	453	155	171
4-1/8	12.4	20.7	33.0	18.0	29.8	47.0	332	360	590	641	219	240
5-1/8	19.4	32.3	51.4	32.3	53.5	84.3	517	562	1060	1150	390	429
6-1/8	27.9	46.4	73.9	52.2	86.3	136	744	807	1710	1860	625	688

R-404A

Line Size	Suction Lines								Liquid Lines				Discharge Lines	
Type L Copper OD (Inches)	Velocity = 1500 fpm				Δt = 1°F Δp = 0.48 psi	Δp = 0.70 psi	Δp = 0.97 psi	Δp = 1.3 psi	Velocity = 150 fpm		Δt = 1°F, Δp = 2.2 psi		Δt = 1°F, Δp = 3.6 psi	
	Suction Temperature (°F) -40	-20	0	20	Suction Temperature (°F) -40	-20	0	20	Suction Temperature (°F) -20	20	-20	20	Suction Temperature (°F) -20	20
3/8	0.09	0.15	0.24	0.37	0.02	0.04	0.06	0.10	1.47	1.61	0.72	0.79	0.40	0.44
1/2	0.17	0.29	0.46	0.70	0.06	0.10	0.15	0.23	2.81	3.09	1.73	1.90	0.94	1.05
5/8	0.28	0.46	0.73	1.12	0.11	0.18	0.29	0.44	4.52	4.96	3.27	3.59	1.77	1.96
7/8	0.58	0.96	1.52	2.33	0.29	0.49	0.77	1.16	9.38	10.3	8.69	9.53	4.63	5.12
1-1/8	0.99	1.64	2.60	3.98	0.60	0.99	1.56	2.35	16.0	17.5	17.7	19.4	9.33	10.3
1-3/8	1.50	2.49	3.95	6.05	1.05	1.74	2.73	4.10	24.4	26.7	31.0	34.0	16.2	18.0
1-5/8	2.13	3.53	5.60	8.57	1.67	2.76	4.32	6.50	34.5	37.8	49.1	53.9	25.6	28.3
2-1/8	3.70	6.13	9.74	14.9	3.49	5.74	8.99	13.5	60.0	65.8	102	112	52.8	58.4
2-5/8	5.70	9.46	15.0	23.0	6.19	10.2	15.9	23.9	92.5	101	181	199	92.9	103
3-1/8	8.14	13.5	21.4	32.8	9.92	16.3	25.4	38.1	132	145	289	317	148	164
3-5/8	11.0	18.3	29.0	44.4	14.8	24.2	37.8	56.6	179	196	431	472	219	243
4-1/8	14.3	23.7	37.7	57.7	20.9	34.2	53.4	79.9	232	255	608	667	308	341
5-1/8	22.3	37.0	58.7	89.9	37.5	61.4	95.6	143	362	397	1090	1200	549	608
6-1/8	32.1	53.2	84.4	129	60.4	98.8	154	230	520	570	1750	1920	880	974

R-507

Line Size	Suction Lines								Liquid Lines				Discharge Lines	
Type L Copper OD (Inches)	Velocity = 1500 fpm				Δt = 1°F Δp = 0.50 psi	Δp = 0.72 psi	Δp = 1.0 psi	Δp = 1.3 psi	Velocity = 150 fpm		Δt = 1°F, Δp = 2.2 psi		Δt = 1°F, Δp = 3.6 psi	
	Suction Temperature (°F) -40	-20	0	20	Suction Temperature (°F) -40	-20	0	20	Suction Temperature (°F) -20	20	-20	20	Suction Temperature (°F) -20	20
3/8	0.10	0.16	0.25	0.38	0.03	0.04	0.07	0.10	1.44	1.58	0.71	0.79	0.40	0.45
1/2	0.18	0.30	0.47	0.72	0.06	0.10	0.16	0.24	2.75	3.02	1.71	1.88	0.95	1.05
5/8	0.29	0.48	0.76	1.16	0.11	0.19	0.30	0.45	4.42	4.85	3.23	3.55	1.78	1.97
7/8	0.61	1.00	1.58	2.41	0.30	0.50	0.79	1.18	9.16	10.1	8.58	9.43	4.65	5.16
1-1/8	1.03	1.70	2.69	4.11	0.62	1.02	1.60	2.40	15.6	17.2	17.5	19.2	9.38	10.4
1-3/8	1.57	2.59	4.10	6.26	1.09	1.79	2.80	4.20	23.8	26.1	30.6	33.6	16.3	18.1
1-5/8	2.22	3.67	5.81	8.86	1.73	2.84	4.43	6.64	33.7	37.0	48.4	53.2	25.7	28.5
2-1/8	3.87	6.39	10.1	15.4	3.61	5.92	9.22	13.8	58.6	64.4	101	111	53.0	58.8
2-5/8	5.97	9.85	15.6	23.8	6.42	10.5	16.3	24.4	90.3	99.2	179	196	93.4	104
3-1/8	8.52	14.1	22.2	33.9	10.3	16.8	26.1	38.9	129	142	286	314	149	165
3-5/8	11.5	19.0	30.1	45.9	15.3	25.0	38.8	57.9	174	192	425	467	220	244
4-1/8	15.0	24.7	39.1	59.7	21.6	35.3	54.7	81.6	227	249	600	659	310	343
5-1/8	23.3	38.5	60.9	93.0	38.8	63.2	98.0	146	353	388	1070	1180	552	611
6-1/8	33.5	55.4	87.6	134	62.6	102	158	234	508	558	1730	1900	884	979

R-717

Steel Line Size		Suction Lines								Liquid Lines				Discharge Lines	
IPS	SCH	Velocity = 1500 fpm				Δt = 1°F Δp = 0.31 psi	Δp = 0.49 psi	Δp = 0.73 psi	Δp = 1.1 psi	Velocity = 150 fpm		Δt = 1°F, Δp = 2.8 psi		Δt = 1°F, Δp = 3.5 psi	
		Suction Temperature (°F) -40	-20	0	20	Suction Temperature (°F) -40	-20	0	20	Suction Temperature (°F) -20	20	-20	20	Suction Temperature (°F) -20	20
3/8	80	0.14	0.23	0.38	0.59	0.09	0.16	0.26	0.41	12.7	13.0	9.89	10.2	1.73	1.91
1/2	80	0.23	0.39	0.63	0.99	0.19	0.32	0.53	0.81	21.1	21.7	19.6	20.1	3.41	3.76
3/4	80	0.42	0.71	1.17	1.82	0.43	0.74	1.20	1.85	39.0	40.0	44.3	45.5	7.68	8.48
1	80	0.69	1.19	1.94	3.03	0.85	1.46	2.37	3.64	64.8	66.6	87.0	89.4	15.1	16.6
1-1/4	80	1.23	2.12	3.46	5.41	1.84	3.16	5.11	7.84	116	119	187	192	32.3	35.6
1-1/2	80	1.70	2.92	4.77	7.46	2.83	4.85	7.82	12.0	159	164	286	293	49.3	54.4
2	40	3.22	5.54	9.06	14.2	6.65	11.4	18.3	28.0	302	311	665	683	114	126
2-1/2	40	4.59	7.91	12.9	20.2	10.7	18.2	29.3	44.7	431	443	1060	1090	182	201
3	40	7.09	12.2	20.0	31.2	19.0	32.4	51.9	79.1	666	685	1880	1930	322	356
3-1/2	40	9.48	16.3	26.7	41.7	27.9	47.5	76.1	116	891	915	2750	2820	472	520
4	40	12.2	21.0	34.4	53.7	39.0	66.3	106	162	1150	1180	3820	3930	657	724
5	40	19.2	33.0	54.0	84.4	70.9	120	192	292	1800	1850	6910	7100	1190	1310
6	40	27.7	47.7	78.0	122	115	195	311	473	2600	2680	----	----	1920	2110
8	40	48.0	82.6	135	211	237	400	637	969	4510	4630	----	----	3920	4320
10	40	75.6	130	213	333	430	725	1160	1750	7110	7300	----	----	7080	7810
12	40	109	187	305	477	690	1160	1850	2810	----	----	----	----	----	----

Suction Line capacities based on 200 equivalent feet, saturated refrigerant vapor, 60°F liquid (86°F liquid for R-717)
Liquid Line capacities based on 200 equivalent feet, saturated 60°F refrigerant liquid (86°F for R-717)
Discharge Line capacities based on 100 equivalent feet, 105°F condensing temperature, isentropic + 50°F discharge vapor temperature, 25°F superheated vapor entering compressor, 60°F liquid (86°F liquid for R-717)
All line capacities calculated with thermodynamic and thermophysical properties computed using NIST Refprop v6.01 database

Approximate line capacity for other saturation temperature Δt and equivalent length Le:
Line capacity = Table capacity * (Table Le * Actual Δt / Actual Le)$^{0.55}$

Approximate saturation temperature Δt for other line capacities and equivalent lengths Le:
Δt = (Actual Le / Table Le) * (Actual capacity / Table capacity)$^{1.8}$

Carrying Capacity of Air Conditioning Lines - Tons of Refrigeration

R-22

Line Size	Suction Lines		Liquid Lines		Discharge Lines
Type L Copper OD (Inches)	Velocity= 1500 fpm	Δt = 1°F Δp = 1.4 psi	Velocity= 150 fpm	Δt = 1°F Δp = 2.9 psi	Δt = 1°F Δp = 3.0 psi
	Suction Temperature = 40°F				
3/8	0.41	0.17	1.93	1.60	0.37
1/2	0.79	0.41	3.70	3.83	0.88
5/8	1.27	0.77	5.94	7.21	1.66
7/8	2.64	2.02	12.3	19.1	4.35
1-1/8	4.50	4.09	21.0	38.7	8.78
1-3/8	6.85	7.13	32.0	67.5	15.3
1-5/8	9.69	11.3	45.3	107	24.1
2-1/8	16.9	23.4	78.8	222	49.8
2-5/8	26.0	41.3	121	392	87.8
3-1/8	37.1	65.8	173	626	140
3-5/8	50.2	97.8	234	930	207
4-1/8	65.3	138	305	1310	292
5-1/8	102	246	475	2350	520
6-1/8	146	395	683	3770	834

R-134a

Line Size	Suction Lines		Liquid Lines		Discharge Lines
Type L Copper OD (Inches)	Velocity= 1500 fpm	Δt = 1°F Δp = 0.96 psi	Velocity= 150 fpm	Δt = 1°F Δp = 2.1 psi	Δt = 1°F Δp = 2.2 psi
	Suction Temperature = 40°F				
3/8	0.26	0.10	1.82	1.23	0.26
1/2	0.51	0.25	3.47	2.94	0.62
5/8	0.81	0.46	5.58	5.54	1.16
7/8	1.68	1.23	11.6	14.7	3.05
1-1/8	2.87	2.49	19.7	29.9	6.17
1-3/8	4.37	4.35	30.1	52.2	10.7
1-5/8	6.19	6.89	42.6	82.7	17.0
2-1/8	10.8	14.3	74.1	172	35.1
2-5/8	16.6	25.3	114	304	61.9
3-1/8	23.7	40.4	163	486	98.6
3-5/8	32.1	60.0	220	723	146
4-1/8	41.7	84.7	287	1020	206
5-1/8	65.0	151	447	1830	367
6-1/8	93.4	243	642	2940	589

R-407C

Line Size	Suction Lines		Liquid Lines		Discharge Lines
Type L Copper OD (Inches)	Velocity= 1500 fpm	Δt = 1°F Δp = 1.4 psi	Velocity= 150 fpm	Δt = 1°F Δp = 3.3 psi	Δt = 1°F Δp = 3.5 psi
	Suction Temperature = 40°F				
3/8	0.38	0.16	1.77	1.64	0.42
1/2	0.72	0.38	3.38	3.90	0.99
5/8	1.15	0.72	5.43	7.33	1.86
7/8	2.39	1.89	11.3	19.4	4.88
1-1/8	4.08	3.82	19.2	39.3	9.85
1-3/8	6.21	6.67	29.3	68.5	17.1
1-5/8	8.79	10.5	41.4	108	27.0
2-1/8	15.3	21.9	72.1	225	55.8
2-5/8	23.6	38.6	111	397	98.3
3-1/8	33.7	61.6	159	633	156
3-5/8	45.5	91.5	215	941	232
4-1/8	59.2	129	279	1330	326
5-1/8	92.2	230	435	2370	581
6-1/8	133	370	625	3810	932

Suction Line capacities based on 100 equivalent feet, saturated refrigerant vapor, 100°F liquid
Liquid Line capacities based on 100 equivalent feet, saturated 100°F refrigerant liquid
Discharge Line capacities based on 100 equivalent feet, 105°F condensing temperature, isentropic + 50°F discharge vapor temperature, 25°F superheated vapor entering compressor, 60°F liquid
All line capacities calculated with thermodynamic and thermophysical properties computed using NIST Refprop v6.01 database

Thermodynamic Terms

Types of Energy
potential: energy due to relative position.
kinetic: energy due to relative velocity.
internal: the sum of all potential and kinetic energies.
heat: energy transferred between system and surroundings due to temperature difference.
work: energy transferred between system and surroundings due to pressure difference.

Heat Units
calorie: energy required to raise one gram of water by 1°C.
BTU: energy required to raise one pound of water by 1°F.

Thermodynamic Systems
closed: energy can cross system boundaries, but mass cannot.
open: both energy and mass can cross system boundaries.
isolated: neither energy nor mass can cross system boundaries.

States
saturation pressure (vapor pressure): pressure at which a phase change will take place at a given temperature.
saturation temperature: temperature at which a phase change will take place at a given pressure.
subcooled liquid: liquid at a temperature below its saturation temperature.
superheated vapor: vapor at a temperature above its saturation temperature.
critical point: saturated state where the liquid and vapor phases become indistinguishable.
triple point: saturated state where the solid, liquid and vapor phases are in equilibrium.

Thermodynamic Properties
mass: the property of a body that is a measure of its inertia, causing it to have weight in a gravitational field.
temperature: a measure of the relative hotness or coldness of a substance.
pressure: force per unit area.
density: the amount of mass of a substance within a unit volume.
specific volume: the amount of space occupied by a unit mass of a substance.
internal energy: sum of all potential and kinetic energies in a substance.
enthalpy: the total useful energy in a substance.
entropy: a measure of energy which is no longer available to perform useful work.
specific heat: the amount of energy necessary to raise the temperature of a substance under constant pressure (Cp) or constant volume (Cv).
latent heat: energy necessary to produce a change in phase without causing a temperature change.
sensible heat: energy that changes temperature.

Thermodynamic Processes
adiabatic: no heat crosses the system boundary
isenthalpic (throttling): constant enthalpy
isentropic: constant entropy
isobaric: constant pressure
isochoric (isometric): constant volume
isothermal: constant temperature

Idealized Thermodynamic Cycles

Vapor Cycles
Carnot: Isentropic compression; isobaric/isothermal heat addition (vaporization); isentropic expansion; isobaric/isothermal heat rejection (condensation). This cycle, though not practical to implement, represents the maximum efficiency attainable from any heat engine.
Rankine: Isentropic compression; isobaric heat addition; isobaric/isothermal heat addition (vaporization); isentropic expansion; isobaric/isothermal heat rejection (condensation). This cycle is closely approximated in actual steam turbine plants.

Combustion Cycles
Otto: Isentropic compression; isochoric heat addition; isentropic expansion; isochoric heat rejection.
Diesel: Isentropic compression; isobaric heat addition; isentropic expansion; isochoric heat rejection.
Brayton: Isentropic compression; isobaric heat addition; isentropic expansion; isobaric heat rejection.
Ericcson: Isothermal compression; isobaric heat addition; isothermal expansion; isobaric heat rejection.
Stirling: Isothermal compression with heat rejection; isochoric heat addition; isothermal expansion with heat addition; isochoric heat rejection.

Refrigeration Cycles
Reversed Carnot: Isentropic compression; isobaric/isothermal heat rejection (condensation); isentropic expansion; isobaric/isothermal heat addition (evaporation).
Vapor Compression: Isentropic compression; isobaric heat rejection; isobaric/isothermal heat rejection (condensation); isenthalpic expansion; isobaric/isothermal heat addition (evaporation). This is the idealized cycle for most modern air conditioning and refrigeration systems.
Reversed Brayton: Isentropic compression; isobaric heat rejection; isentropic expansion; isobaric heat addition. This cycle uses air as a refrigerant.
Reversed Stirling: Isothermal compression with heat rejection; isochoric heat rejection; isothermal expansion with heat addition; isochoric heat addition.

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Form 5-162-702

Refrigeration Engineer Quick Reference

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Fluid Flow Equations

Bernoulli equation:

$$\frac{p_1 g_c}{\gamma} + \frac{v_1^2}{2g} + z_1 = \frac{p_2 g_c}{\gamma} + \frac{v_2^2}{2g} + z_2; \quad \gamma = \rho g$$

Reynolds Number:

$$R_e = \frac{vD}{\nu} = \frac{vD\rho}{\mu g_c}$$

Colebrook's equation:

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left[\frac{\varepsilon/D}{3.7} + \frac{2.51}{R_e\sqrt{f}}\right]$$

Darcy-Weisbach equation:

$$h_f = f\frac{L_e}{D}\frac{v^2}{2g}$$

Orifice equation (incompressible flow):

$$m = C_f A_o\sqrt{2g_c\rho\Delta p};\ R_e > 250$$

Orifice equation (vapor flow):

$$m = C_f A_o\sqrt{\frac{2k}{k-1}p_u g_c \rho_u\left(\frac{p_d}{p_u}\right)\left[1-\left(\frac{p_d}{p_u}\right)^{(k-1)/k}\right]}$$

where $\frac{p_d}{p_u}$ **> critical pressure ratio**

Critical pressure ratio:

$$\frac{p_d}{p_u} = \left(\frac{2}{k+1}\right)^{k/(k-1)}$$

Nomenclature		I-P	S-I
A_o	orifice area	ft²	m²
C_f	flow coefficient	---	---
D	diameter	ft	m
f	friction factor	---	---
g_c	gravitational conversion factor	32.174 lb_m-ft/lb_f-sec²	1.0
k	specific heat ratio	---	---
h_f	head loss due to friction	ft	m
L_e	equivalent length	ft	m
m	mass flow rate	lb_m/sec	kg/sec
p	pressure	lb_f/ft²	Pa
R_e	Reynold's Number	---	---
v	velocity	ft/sec	m/sec
z	height	ft	m
ε	effective roughness	ft	m
γ	specific weight	lb_m/ft²-sec²	N/m³
μ	absolute viscosity	lb_f-sec/ft²	Pa-sec
ν	kinematic viscosity	ft²/sec	m²/sec
ρ	density	lb_m/ft³	kg/m³

Subscripts: u = upstream; d = downstream

Physical Constants		I-P	S-I
g	standard acceleration due to gravity	32.1740 ft/sec²	9.80665 m/sec²
k	Boltzmann's constant	5.657308×10^{-24} ft-lb_f/°R	1.380650×10^{-26} kJ/°K
N_A	Avogadro's constant	$2.73159766 \times 10^{26}$ / lb mol	$6.02214199 \times 10^{26}$ / kg mol
R	universal gas constant	1545.349 ft-lb_f/lb mol-°R	8.314471 kJ/kg mol-°K

Refrigerant Data

ASHRAE Number	Chemical Name	Sporlan Letter Designation	Color Designation (PMS No.)[1]	ASHRAE 34 Safety Group	CAS Registry Number	Critical Values[2] Temperature (°F)	Pressure (psia)	Specific Vol (ft³/lb_m)	Molecular Weight
R-10	tetrachloromethane (carbon tetrachloride)			B1	56-23-5	542.03	661.37	0.0287	153.82
R-11	trichlorofluoromethane	H	Orange (021)	A1	75-69-4	388.33	639.27	0.0289	137.37
R-12	dichlorodifluoromethane	F	White (N/A)	A1	75-71-8	233.55	599.89	0.0284	120.91
R-12B1	bromochlorodifluoromethane (halon 1211)				353-59-3	308.84	594.94	0.0225	165.36
R-13	chlorotrifluoromethane	E	Light Blue (2975)	A1	75-72-9	83.71	562.31	0.0275	104.46
R-13B1	bromotrifluoromethane (halon 1301)	T	Pinkish-Red/Coral (177)	A1	75-63-8	152.60	574.90	0.0215	148.91
R-14	tetrafluoromethane (carbon tetrafluoride)		Yellow-Brown/Mustard (124)	A1	75-73-0	-50.15	543.89	0.0256	88.01
R-20	trichloromethane (chloroform)				67-66-3	504.23	794.81	0.0324	119.38
R-21	dichlorofluoromethane			B1	75-43-4	353.21	751.30	0.0306	102.92
R-22	chlorodifluoromethane	V	Light Green (352)	A1	75-45-6	205.06	723.74	0.0306	86.47
R-22B1	bromodifluoromethane (halon 1201)				1511-62-2	281.89	744.33	0.0204	130.92
R-23	trifluoromethane	G	Light Blue-Gray (428)	A1	75-46-7	78.66	701.40	0.0305	70.01
R-30	dichloromethane (methylene chloride)			B2	75-09-2	455.27	881.83	0.0357	84.93
R-31	chlorofluoromethane				593-70-4	305.17	744.20	0.0371	68.48
R-32	difluoromethane (methylene fluoride)			A2	75-10-5	172.59	838.61	0.0378	52.02
R-40	chloromethane (methyl chloride)			B2	74-87-3	289.49	965.95	0.0446	50.49
R-41	fluoromethane (methyl fluoride)				593-53-3	111.43	855.29	0.0506	34.03
R-50	methane			A3	74-82-8	-116.70	666.40	0.0988	16.04
R-110	hexachloroethane				67-72-1	808.3	571	0.0284	236.74
R-113	1,1,2-trichloro-1,2,2-trifluoroethane		Dark Purple/Violet (266)	A1	76-13-1	417.31	492.00	0.0286	187.37
R-114	1,2-dichloro-1,1,2,2-tetrafluoroethane	B	Dark Blue/Navy (302)	A1	76-14-2	294.22	472.39	0.0276	170.92
R-115	chloropentafluoroethane			A1	76-15-3	175.91	452.52	0.0261	154.47
R-116	hexafluoroethane		Dark Grey (424)	A1	76-16-4	67.78	441.20	0.0258	138.01
R-123	2,2-dichloro-1,1,1-trifluoroethane		Light Blue-Gray (428)	B1	306-83-2	362.63	531.10	0.0291	152.93
R-124	2-chloro-1,1,1,2-tetrafluoroethane	M	Deep Green (335)	A1	2837-89-0	252.10	525.66	0.0286	136.48
R-125	pentafluoroethane		Medium Brown/Tan (465)	A1	354-33-6	151.12	526.34	0.0280	120.02
R-130	1,1,2,2-tetrachloroethane				79-34-5	730.5	847.0		167.85
R-134a	1,1,1,2-tetrafluoroethane	J	Light Blue (2975)	A1	811-97-2	213.91	588.75	0.0313	102.03
R-141b	1,1-dichloro-1-fluoroethane				1717-00-6	399.56	616.41	0.0348	116.95
R-142b	1-chloro-1,1-difluoroethane			A2	75-68-3	278.78	597.99	0.0368	100.50
R-143a	1,1,1-trifluoroethane			A2	420-46-2	163.20	547.60	0.0370	84.04
R-150	1,2-dichloroethane				107-06-2	559.1	778.9	0.0364	98.96
R-150a	1,1-dichloroethane				75-34-3	481.7	735.3		98.96
R-152a	1,1-difluoroethane			A2	75-37-6	235.87	655.10	0.0435	66.05
R-160	chloroethane (ethyl chloride)				75-00-3	369.1	764		64.51
R-160B1	ethyl bromide (halon 2001)				74-96-4	447.3	903.6		108.96
R-161	fluoroethane (ethyl fluoride)				353-36-6	216.0	682		48.06
R-170	ethane	K		A3	74-84-0	89.92	706.59	0.1120	30.07
R-227ea	1,1,1,2,3,3,3-heptafluoropropane				431-89-0	217.04	432.21	0.0276	170.03
R-236ea	1,1,1,2,3,3-hexafluoropropane				431-63-0	282.72	507.92	0.0285	152.04
R-236fa	1,1,1,3,3,3-hexafluoropropane				690-39-1	256.86	464.12	0.0291	152.04
R-245ca	1,1,2,2,3-pentafluoropropane				679-86-7	345.96	569.27	0.0306	134.05
R-245fa	1,1,1,3,3-pentafluoropropane			A1	460-73-11	309.29	527.94	0.0310	134.05
R-C270	cyclopropane				75-19-4	257.27	809.23	0.0617	42.08
R-290	propane			A3	74-98-6	206.06	616.07	0.0706	44.10
R-C318	octafluorocyclobutane			A1	115-25-3	239.41	402.84	0.0258	200.04
R-600	n-butane			A3	106-97-8	305.62	550.56	0.0703	58.12
R-600a	2-methyl propane (isobutane)			A3	75-28-5	274.46	527.94	0.0714	58.12
R-601	n-pentane				109-66-0	385.8	487	0.0690	72.15
R-601a	2-methyl butane (isopentane)				78-78-4	370.0	490	0.0679	72.15
R-610	ethyl ether				60-29-7	380.57	527.94	0.0609	74.12
R-611	methyl formate			B2	107-31-3	416.39	870.23	0.0459	60.05
R-630	methyl amine				74-89-5	314.4	1082.0	0.0714	31.06
R-631	ethyl amine				75-04-7	361.4	815.11	0.0632	45.08
R-702n	normal hydrogen			A3	1333-74-0	-399.93	190.75	0.5320	2.02
R-704	helium			A1	7440-59-7	-450.31	32.99	0.2300	4.00
R-717	ammonia	A	Silver	B2	7664-41-7	269.99	1643.7	0.0682	17.03
R-718	water/steam			A1	7732-18-5	705.18	3199.2	0.0497	18.02
R-720	neon			A1	7440-01-9	-379.58	388.50	0.0332	20.18
R-728	nitrogen			A1	7727-37-9	-232.52	492.81	0.0510	28.01
R-729	air					-220.96	548.97	0.0529	28.97
R-732	oxygen				7782-44-7	-181.42	731.42	0.0367	32.00
R-740	argon			A1	7440-37-1	-188.48	704.88	0.0302	39.95
R-744	carbon dioxide			A1	124-38-9	87.76	1069.9	0.0342	44.01
R-744A	nitrous oxide				10024-97-2	97.61	1050.1	0.0353	44.01
R-764	sulfur dioxide			B1	7446-09-5	315.77	1142.9	0.0305	64.06
R-1120	trichloroethene (trielene)				79-01-6	568	712	0.0312	131.39
R-1130	trans-1,2-dichloroethene (dielene)				156-60-5	469.9	795		96.95
R-1132a	1,1-difluoroethene (vinylidene fluoride)				75-38-7	85.46	646.62	0.0385	64.04
R-1140	chloroethene (vinyl chloride)			B3	75-01-4	305.3	746.9		62.50
R-1150	ethene (ethylene)			A3	74-85-1	48.55	731.00	0.0748	28.05
R-1270	propene (propylene)			A3	115-07-1	198.36	676.54	0.0717	42.08

Refrigerant Blends

ASHRAE Number	Composition (mass percentages)	Sporlan Letter Designation	Color Designation (PMS No.)[1]	ASHRAE 34 Safety Group	Trade Name	Critical Values[2] Temperature (°F)	Pressure (psia)	Specific Vol (ft³/lb_m)	Molecular Weight
R-401A	R-22/R-152a/R-124 (53/13/34)	X	Pinkish-Red/Coral (177)	A1	MP39	221.48	669.03	0.0324	94.44
R-401B	R-22/R-152a/R-124 (61/11/28)	F	Yellow-Brown/Mustard (124)	A1	MP66	218.38	679.07	0.0322	92.84
R-402A	R-125/R-290/R-22 (60/2/38)	L	Light Brown/Sand (461)	A1	HP80	168.85	614.11	0.0294	101.55
R-402B	R-125/R-290/R-22 (38/2/60)	R	Green-Brown/Olive (385)	A1	HP81	181.45	656.35	0.0299	94.71
R-403A	R-290/R-22/R-218 (5/75/20)			A1	ISCEON® 69-S	196.2	680		91.99
R-403B	R-290/R-22/R-218 (5/56/39)			A1	ISCEON® 69-L	191.7	638		103.26
R-404A	R-125/R-143a/R-134a (44/52/4)	S	Orange (021)	A1	HP62, FX-70	161.86	541.71	0.0328	97.60
R-405A	R-22/R-152a/R-142b/R-C318 (45/7/5.5/42.5)				GREENCOOL G2015	222.8	622		111.91
R-406A	R-22/R-600a/R-142b (55/4/41)			A2	GHG	241.7	708		89.86
R-406B	R-22/R-600a/R-142b (65/4/31)				GHG-HP				88.58
R-407A	R-32/R-125/R-134a (20/40/40)	V	Lime Green (368)	A1	Klea® 60	179.44	650.77	0.0302	90.11
R-407B	R-32/R-125/R-134a (10/70/20)		Cream (156)	A1	Klea® 61	165.88	592.21	0.0285	102.94
R-407C	R-32/R-125/R-134a (23/25/52)	N	Medium Brown (471)	A1	Klea® 66, Suva 9000	186.89	672.11	0.0312	86.20
R-407D	R-32/R-125/R-134a (15/15/70)		Dark Brown/Chocolate (450)	A1		196.82	650.21	0.0315	90.96
R-407E	R-32/R-125/R-134a (25/15/60)			A1		191.78	686.59	0.0320	83.78
R-408A	R-125/R-143a/R-22 (7/46/47)	R	Medium Purple (248)	A1	FX-10	182.30	629.46	0.0325	87.02
R-409A	R-22/R-124/R-142b (60/25/15)	F	Medium Brown/Tan (465)	A1	FX-56	224.46	667.17	0.0316	97.43
R-409B	R-22/R-124/R-142b (65/25/10)			A1	FX-57	219.84	683.24	0.0313	96.67
R-410A	R-32/R-125 (50/50)	Z	Rose (507)	A1	AZ-20, Suva® 9100, Puron®	158.30	691.81	0.0290	72.59
R-411A	R-1270/R-22/R-152a (1.5/87.5/11)		Dark Purple/Violet (266)	A2	GREENCOOL G2018a	210.31	718.46	0.0329	82.36
R-411B	R-1270/R-22/R-152a (3/94/3)		Blue-Green/Teal (326)	A2	GREENCOOL G2018b	204.71	717.54	0.0322	83.07
R-411C +	R-1270/R-22/R-152a (3/95.5/1.5)				GREENCOOL G2018c	203.9	718		83.44
R-412A	R-22/R-218/R-142b (70/5/25)			A2	Arcton TP5R	225.5	708		92.17
R-413A	R-218/R-134a/R-600a (9/88/3)			A2	ISCEON® 49	214.5	615		103.95
R-414A	R-22/R-124/R-142b/R-600a (51/28.5/16.5/4)			A1	GHG-X4, Autofrost, Chill-It	231.3	682		96.93
R-414B	R-22/R-124/R-142b/R-600a (50/39/9.5/1.5)		Medium Blue (2995)		Hot Shot, Kar Kool	226.4	666		101.59
R-416A	R-134a/R124/R-600 (59/39.5/1.5)		Yellow-Green/Lime (381)		FRIGC (FR-12)	226.8	583		111.92
R-417A	R-125/R-134a/R-600 (46.6/50/3.4)				ISCEON® 59, NU-22	193.8	595		106.75
R-500	R-12/R-152a (73.8/26.2)	D	Yellow (109)	A1	Carrene #7	215.87	605.25	0.0326	99.30
R-501	R-22/R-12 (75/25)			A1		205.15	690.97	0.0304	93.10
R-502	R-22/R-115 (48.8/51.2)	R	Light Purple/Lavender (251)	A1		177.31	582.84	0.0282	111.63
R-503	R-23/R-13 (40.1/59.9)	W	Blue-Green/Aqua (3268)			65.17	618.54	0.0290	87.25
R-504	R-32/R-115 (48.2/51.8)					143.84	643.80	0.0317	79.25
R-505	R-12/R-31 (78/22)					244.0	686		103.48
R-506	R-31/R-114 (55.1/44.9)					288.0	748		93.69
R-507A (R-507)	R-125/R-143a (50/50)	P	Blue-Green/Teal (326)	A1	AZ-50	159.34	538.78	0.0325	98.86
R-508A (R-508)	R-23/R-116 (39/61)			A1	Klea® 5R3	51.81	536.72	0.0279	100.10
R-508B	R-23/R-116 (46/54)	W	Dark Blue/Navy (302)	A1	Suva® 95	53.70	556.11	0.0281	95.39
R-509A (R-509)	R-22/R-218 (44/56)			A1	Arcton TP5R2	189.0	585		123.96

1Refrigerant color designations per ARI Guideline N
2Data obtained from various sources, including: ASHRAE, NIST, and refrigerant manufacturers
+ preliminary ASHRAE Number

ASHRAE 34 refrigerant designation system:
first digit on the right: number of fluorine atoms
second digit on the right: number of hydrogen atoms plus one
third digit on the right: number of carbon atoms minus one (not used when equal to zero)
fourth digit on the right: unsaturated carbon-carbon bonds in the compound (not used when equal to zero)

The lower-case letter that follows the refrigerant designation refers to the form of the molecule when different forms (isomers) are possible, with the most symmetrical form indicated by the number alone. As the form becomes less and less symmetrical, the letters a, b, and c (lower case) are appended.

Conversion Factors

Length
1 ft = **0.3048** meters

Mass
1 lb_m =
- **0.45359237** kg
- **16** ounces (avoir.)
- 14.583333 ounces (troy)
- **7000** grains
- 0.03108095 slugs
- **5.0×10^{-4}** tons (short, US)
- 4.4642857×10^{-4} tons (long, UK)
- **4.5359237×10^{-4}** tonnes (1000 kg)

Temperature
°F =
- **1.8 * °C + 32**
- **°R - 459.67**
- **1.8 * °K - 459.67**

Pressure
1 psi =
- 0.068947573 bar
- 0.0068947573 MPa
- 6.8947573 kPa
- 0.068045964 atm
- 0.070306958 kg_f/cm^2
- 2.0360 in $Hg_{(32°F)}$[1]
- 2.0418 in $Hg_{(60°F)}$[1]
- 2.0360207 in Hg_{conv}
- 51.714933 mm Hg_{conv} (torr)
- 51,714.933 µm Hg_{conv} (microns)
- 27.681 in $H_20_{(39.2°F)}$[1]
- 27.708 in $H_20_{(60°F)}$[1]
- 27.679905 in H_20_{conv}
- 703.06958 mm H_20_{conv}

Volume
1 ft³ =
- 0.028316847 m³
- 28.316847 litre
- 7.4805195 gal (liq. U.S.)

Specific Volume
1 ft³/lb_m =
- 0.062427961 m³/kg
- 62.427961 cm³/g
- 7.4805195 gal (liq. U.S.)/lb_m

Density
1 lb_m/ft³ =
- 16.018463 kg/m³
- 0.016018463 g/cm³
- 0.13368056 lb_m/gal (liq. U.S.)

Energy (work)
1 Btu_{IT}[2] =
- 778.16926 ft-lb_f
- 1055.0559 Joule (watt-sec)
- 0.29307107 watt-hr
- 251.99576 cal_{IT}
- 251.82723 cal_{th}
- 1.0550559×10^{10} ergs
- 0.99933123 Btu_{th}
- 1.0007717 $Btu_{(mean)}$
- 1.0043734 $Btu_{(39°F)}$
- 0.9997575 $Btu_{(59°F)}$
- 0.9996438 $Btu_{(60°F)}$

Power
1 ton, refrigeration[3] =
- **12,000** Btu/hr
- **200** Btu/min
- 3.5168528 kW
- 4.7161772 hp (500 ft-lb_f/sec)
- 4.7142798 hp, electric
- 4.7815890 hp, metric (75 m-kg_f/sec)

Specific Enthalpy
1 Btu_{IT}/lb_m = **2.326** kJ/kg

Specific Entropy
1 Btu_{IT}/lb_m-°R = **4.1868** kJ/kg-°K

Viscosity (absolute)
1 lb_f-sec/ft² =
- 47.88026 Pa-sec (N-sec/m²)
- 478.8026 poise (dyne-sec/cm²)
- 47,880.26 centipoise (mPa-sec)
- 32.17405 lb_m/ft-sec

[1] Conversion factors for mercury and water manometer pressure units are calculated using standard acceleration of gravity at the stated temperature. Additional digits are not justified as the definitions of the units do not take into account compressibility and changes in density caused by the revised temperature scale, ITS-90. Conversion factors for conventional mercury and water manometer pressure units, noted on this chart with subscript "conv", Hg_{conv} and H_20_{conv}, are based on ISO Standard 31-3:1992.

[2] The Fifth International Conference on the Properties of Steam (London, July 1956) defined the International Table calorie as **4.1868** J. Therefore, the exact conversion for the International Table Btu is **1.05505585262** kJ. The notation of International Table on this chart is subscript "IT", and the notation for thermochemical is subscript "th". The thermochemical Btu, Btu_{th}, is based on the thermochemical calorie, cal_{th}, where cal_{th} is defined as **4.184** J.

[3] Ton, *refrigeration* is defined as the rate of cooling provided by melting a ton of ice in one day, with the latent heat of fusion for water defined as 144 Btu/lb_m. A slightly more accurate value for the latent heat of fusion for water is 333.6 kJ/kg (143.4 Btu_{IT}/lb_m). For conversion to other units, 1 ton refrigeration = 12,000 Btu_{IT}/hr is used.

Note: Conversions in **bold** are exact.

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