ORDRE DES INGÉNIEURS DU QUÉBEC

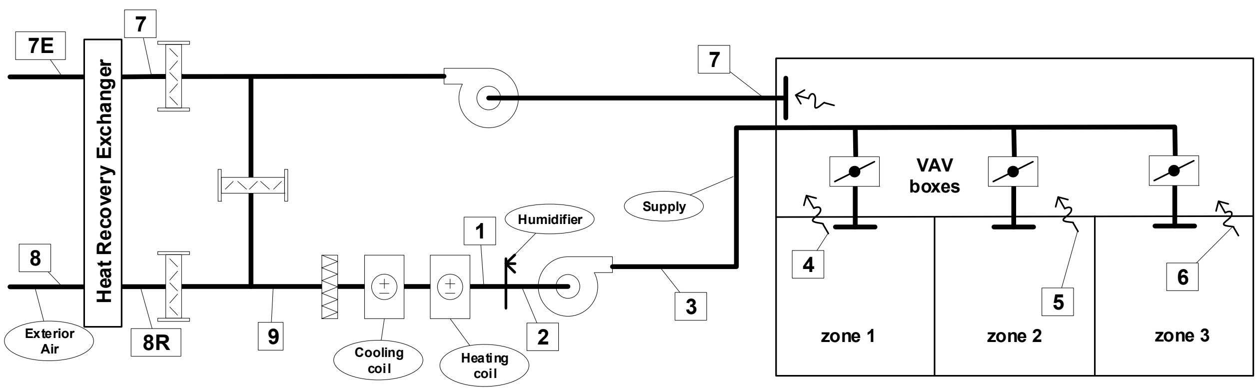
NOVEMBER 2020 SESSION

Open-book examination
Calculators : only authorized models
Duration : 3 hours

16-MC-B1
Environmental control in buildings

Problem #1 (40 %)

The diagram shows a VAV (Variable Air Volume) air-conditioning system.



For the design conditions (the peak of system), the specifications are as follows:

- zones temperature and relative humidity — $t_{Z1,Z2,Z3} = 25°C$ — $\phi = 40$ to 60%
- supply air temperature — $t_s = t_3 = 17°C$
- exterior air state — $t_e = t_8 = 35°C$ — $t_{wb} = 24°C$
- minimum exterior air flow rate — 25% of design fan air flow rate
- air temperature increasing across the supply fan — $\Delta t_v = 1°C$
- air temperature increasing across the return fan — negligible
- air temperature increasing across the plenum — $\Delta t_{fp} = 2°C$
- latent and sensible heat gains for each zone for design conditions (the peak of system):

  - $q_{sens,Z1} = 15$ kW — $q_{lat,Z1} = 8.8$ kW
  - $q_{sens,Z2} = 12$ kW — $q_{lat,Z2} = 2.93$ kW
  - $q_{sens,Z3} = 23.5$ kW — $q_{lat,Z3} = 7.32$ kW

Part A ***without heat recovery exchanger*** *(15%)*

Locate the key air states (*points shown in system diagram*) on the psychrometric chart and determine the dry bulb temperature and relative humidity of each point. Determine also:

A-1 Zones air flow rates and design fan air flow rate;
A-2 Zones temperature and humidity ratio;
A-3 Cooling coil capacity (without heat recovery exchanger).

Part B *(15%)*

The **rotary sensible wheel** is used as heat recovery exchanger with **$\varepsilon = 0.7$**

Summer period Locate the key air states (*points shown in system diagram*) on the psychrometric chart using the data and results from Part A.

B-1 Determine the new cooling coil capacity.

Winter period with the specifications as follows:

- Zone and fan air flow rates ***are equal to 50%*** of the air flow rates determined in Part A
- Exterior air state $t_e = t_8 = -15°C$ $w_8 = 0.0004$ kg/kg$_{\text{dry air}}$
- Zone air states $t_{Z1,Z2,Z3} = 23°C$ $\varphi = 30\%$ $w_{Z1,Z2,Z3} = 0.0052$ kg/kg$_{\text{dry air}}$
- Supply air state $t_3 \geq 18°C$ $w_3 = w_{Z1,Z2,Z3}$

Locate the key air states specific for winter period on the psychrometric chart and determine:

B-2 the preheating coil capacity, if applicable, to avoid a condensation in the rotary sensible wheel;
B-3 heating coil capacity;
B-4 steam rate injected by humidifier.

Part C *(10%)*

The **rotary enthalpy wheel** is used as heat recovery exchanger with **$\varepsilon = 0.8$**

Summer period Locate the key air states (*points shown in system diagram*) on the psychrometric chart using the data and results from Part A.

C-1 Determine the new cooling coil capacity.

Winter period with the specifications from Part B :

Locate the key air states specific for winter period on the psychrometric chart and determine:

C-2 the preheating coil capacity, if applicable, to avoid a condensation in the rotary enthalpy wheel;
C-3 heating coil capacity.

Problem # 2 (15 %)

The monthly electricity bills for the years 2017 and 2018 are presented in the attached table (***gas is used*** *for heating and domestic hot water*). The cooling of the building in the period "April – October" is provided by a centrifugal refrigeration chiller. Therefore, the average electricity consumption for the months January - March and November - December is considered as basic electricity consumption.

The electricity consumption in 2018 is lower than in 2017. This reduction in consumption is partially due to the installation of the new Low-E coating and energy efficient windows.

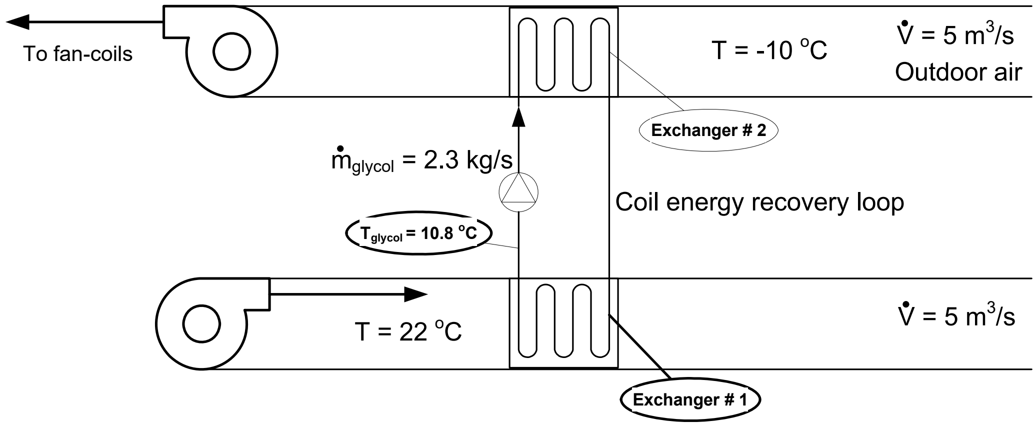
It is also to take into account that the cooling degree-days (above 18 ºC) for the years 2017 and 2018 are respectively 250 and 220. Assuming that the other heat gains in the building are the same in 2017 and 2018, determine:

a) the annual (April – October) chiller energy consumptions for the years 2017 and 2018 (5%);
b) how this decrease in energy consumption is impacted (in kWh) by:
   i. the installation of new windows (5%) and
   ii. the weather conditions (degree days) (5%).

Month	Electricity consumption (kWh)	
	2017	**2018**
January	237 446	236 480
February	224 668	235 690
March	240 913	238 540
April	255 581	248 592
Mai	279 834	272 564
Juin	293 023	283 020
July	323 095	311 560
August	309 988	289 988
September	281 676	274 776
October	260 238	256 238
November	231 550	232 550
December	234 389	233 389
Total	3 172 401	3 113 387

Problem #3 (20 %)

The fan-coil conditioner system serves an entire building. Primary air made up of outdoor air, required to maintain air quality, is supplied to fan-coils by a constant volume air system as illustrated in figure below. The coil energy recovery loop with two glycol-air coils is used to preheat the outdoor air. At a given moment, the data acquisition system shows the results illustrated in figure. Assume that the effectiveness of heat exchanger **#1** is $\varepsilon = 64\%$. Determine:



a) The heat recovery serving to preheat the outdoor air (in kW) *(5 %);*
b) Air temperature leaving the heat exchanger #2 *(5 %);*
c) Effectiveness of heat exchanger #2 *(5 %);*
d) Effectiveness of the coil energy recovery loop with two glycol-air coils *(5 %).*

Assume that:

Specific heat of glycol	$c_p = 3.2$ kJ/kg°C
Air density	$\rho = 1.2$ kg/m^3
Specific heat of air	$c_p = 1.0$ kJ/kg°C

Problem # 4 (25 %)

The refrigeration system includes two evaporators and two condensers operating with R-507A as refrigerant. The heat exchange between two loops (LT and MT) allows the sub-cooling of the R-507A liquid at the outlet of the LT loop condenser.
The following specifications are presented in the attached figure: cooling capacity of evaporators and condensers, evaporation and condensation temperatures and specific states of R-507A in LT and MT loops. The compressors used in the cycle are isentropic. The pressure drop of R-507A in the evaporators, condensers and sub-cooling exchanger are negligible.

Show the refrigeration cycle on the attached p-h diagram (5%) and determine:

a) The R-507A mass flow rates ($\dot{m}_{LT}$, $\dot{m}_{5MT}$, $\dot{m}_{6MT}$, $\dot{m}_{1MT}$) in kg/s (6%);
b) The compressor power inputs in kW (4%);
c) The COP (coefficient of performance) of proposed refrigeration system (4%);

Assume that the exchanger for sub-cooling is cancelled, so the liquid in the 3LT state enters the expansion valve of the LT loop. Therefore, two loops (LT and MT) are changed to become two separate LT and MT systems. The evaporator capacities in these new systems are the same as before this modification. Determine:

d) The new compressor power inputs in the LT and MT systems and new total COP of these two systems (6%).

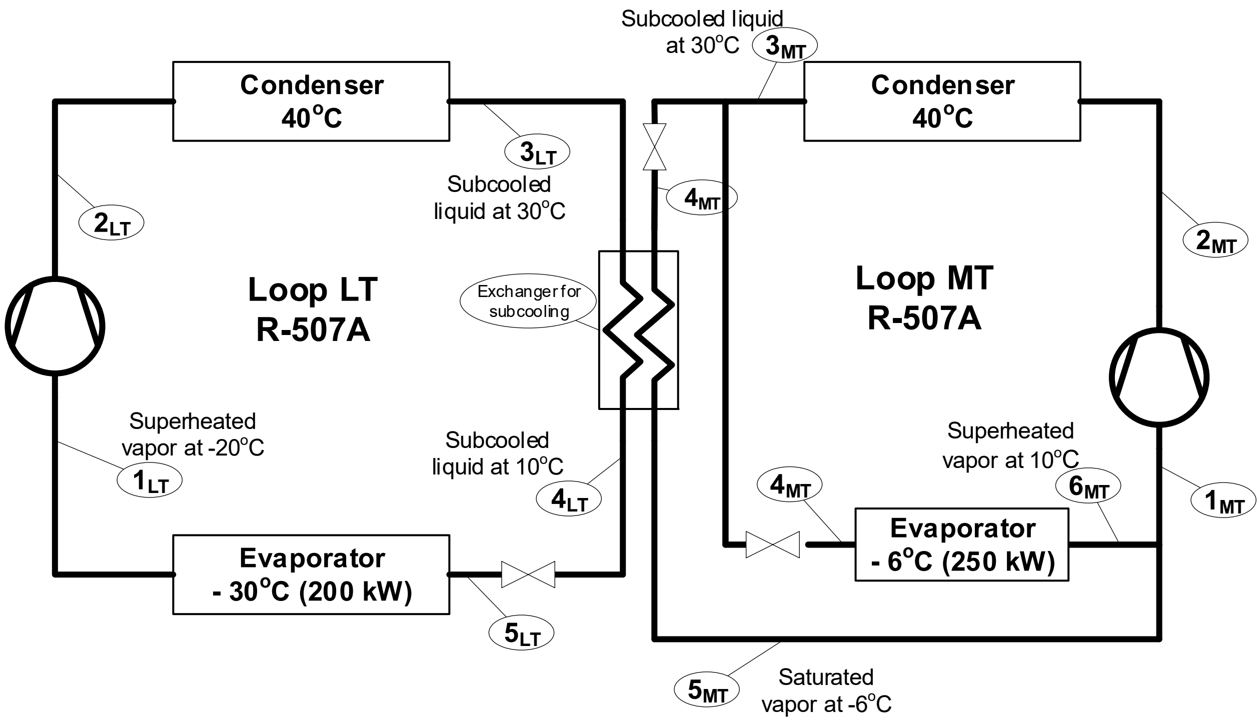

Subcooled liquid
at 30°C
3MT
Condenser
40°C
3LT
Subcooled
liquid at 30°C
2LT
4MT
2MT
Loop LT
R-507A
Exchanger for
subcooling
Loop MT
R-507A
Superheated
vapor at -20°C
1LT
Subcooled
liquid at 10°C
4LT
Superheated
vapor at 10°C
4MT
6MT
1MT
Evaporator
- 30°C (200 kW)
5LT
Evaporator
- 6°C (250 kW)
5MT
Saturated
vapor at -6°C

Chart 1*b* ASHRAE Psychrometric Chart No. 1 (SI) (Reprinted by permission of ASHRAE.)

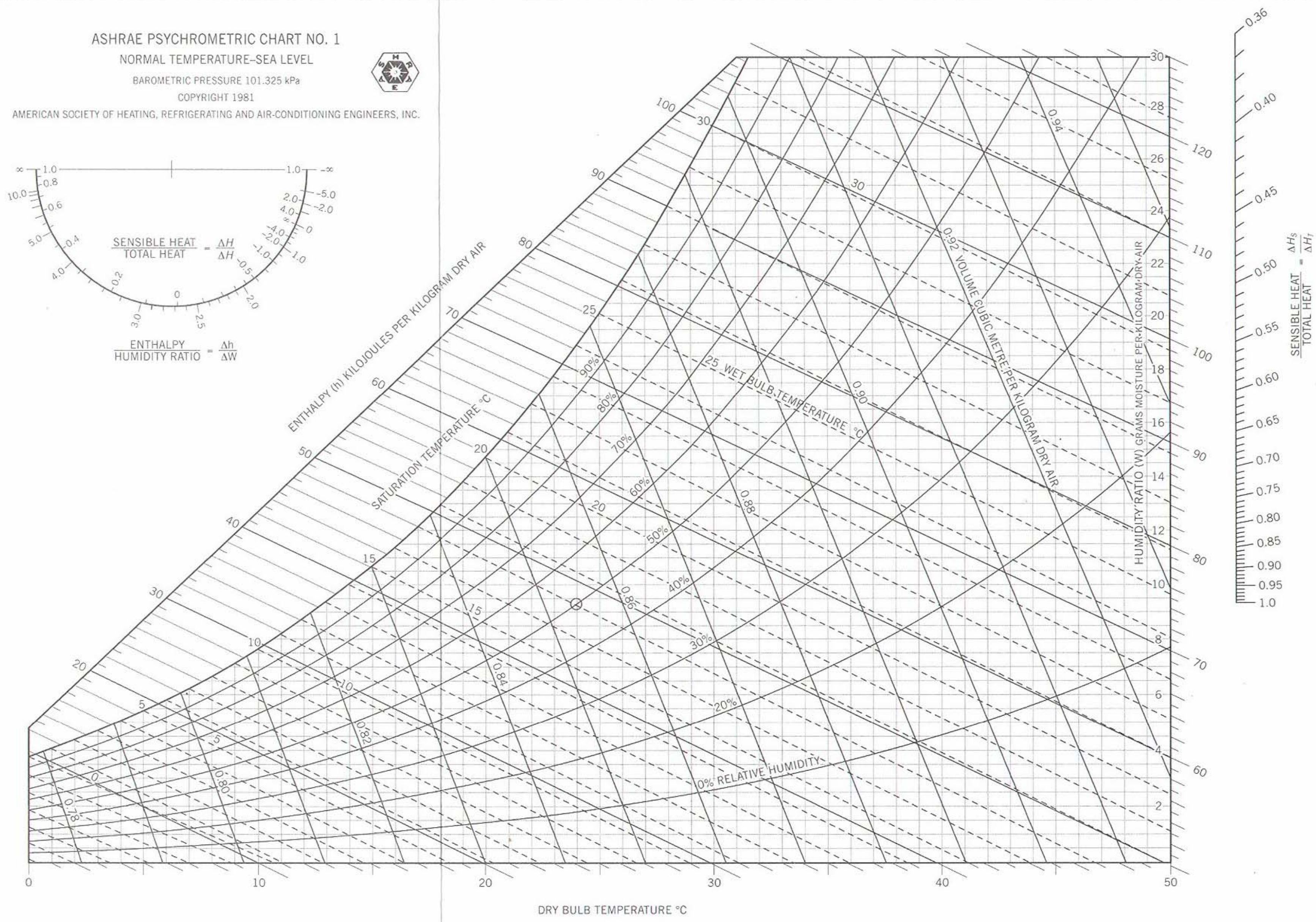
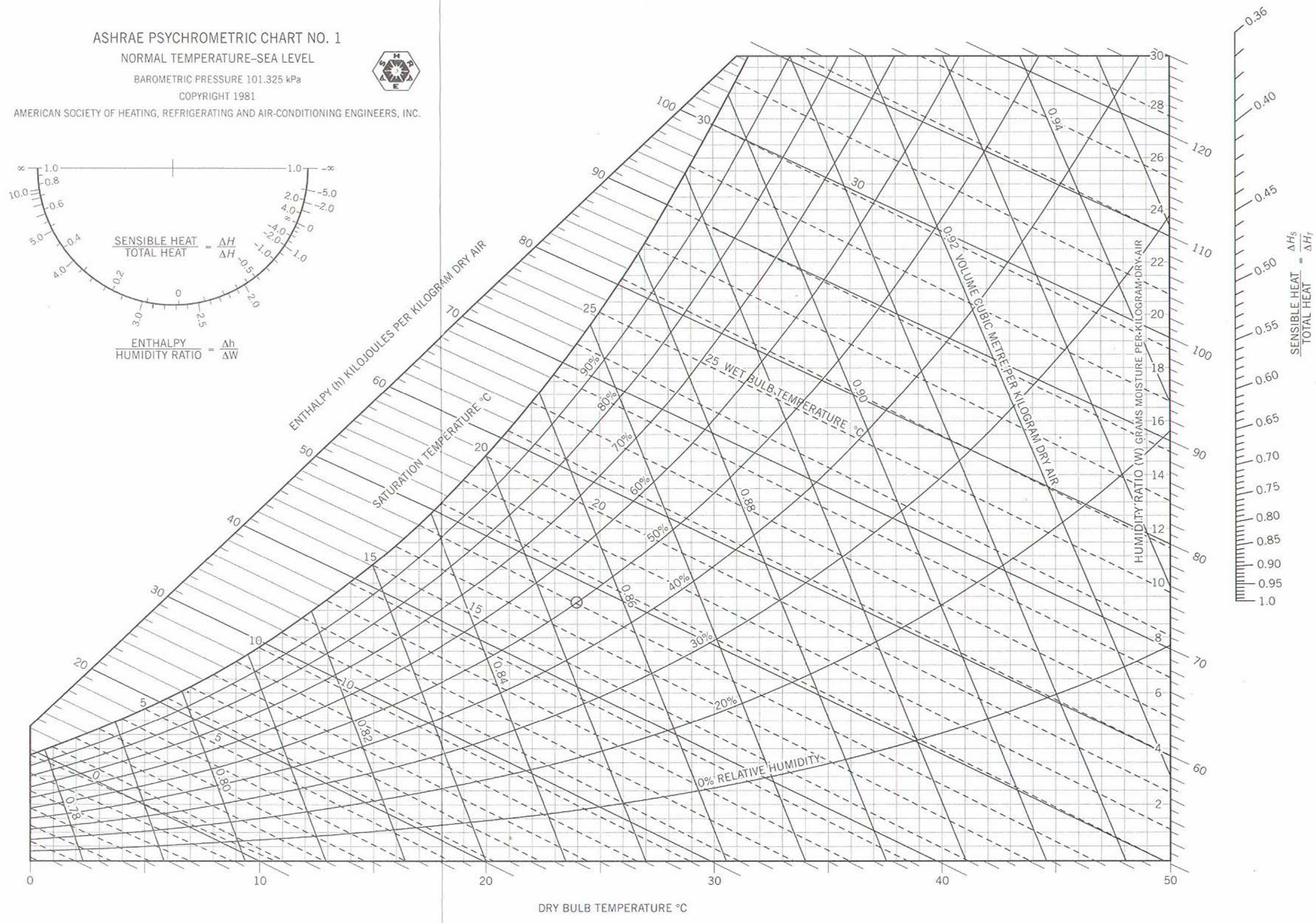


Chart 1*b* ASHRAE Psychrometric Chart No. 1 (SI) (Reprinted by permission of ASHRAE.)

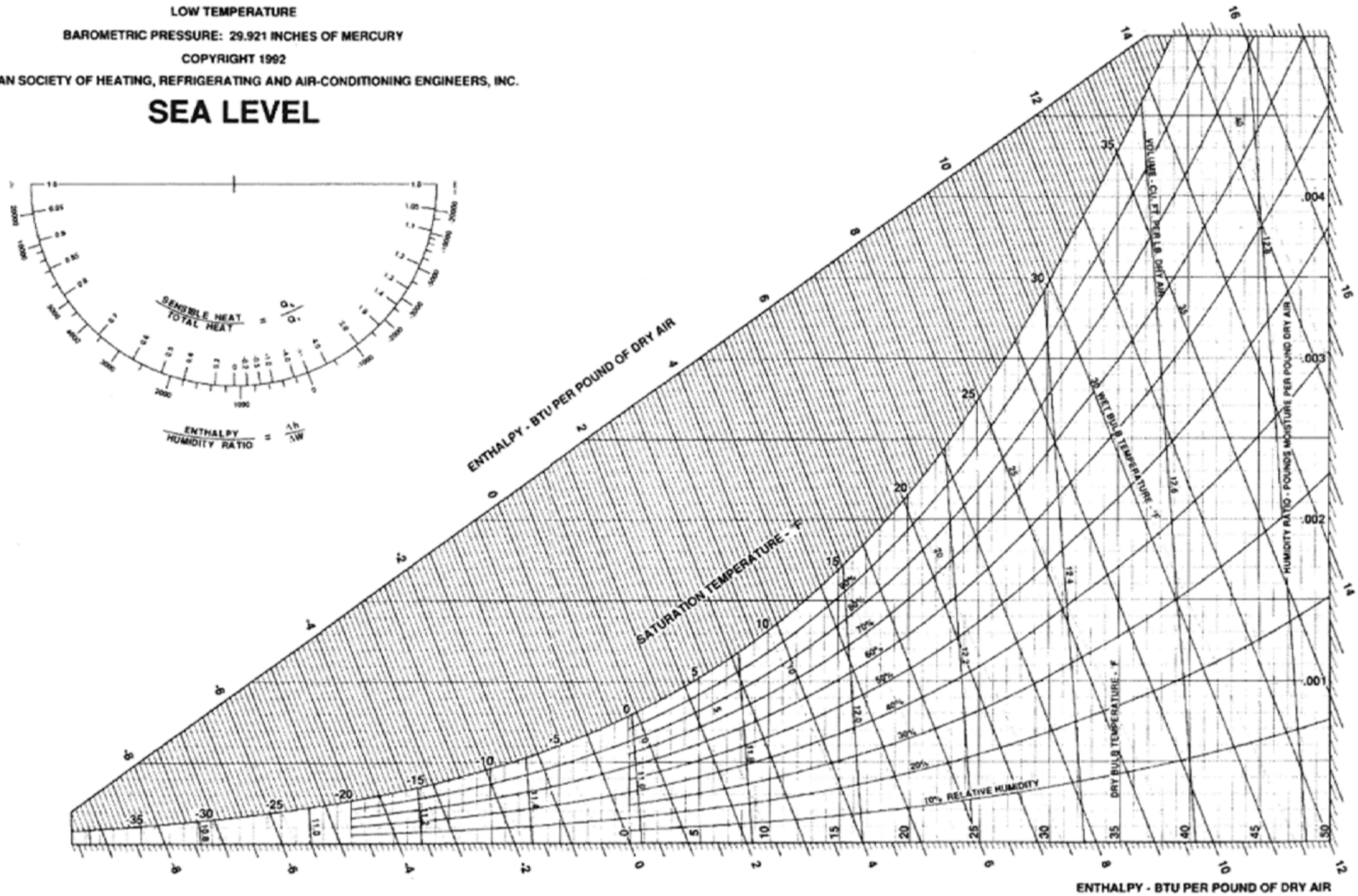


ASHRAE PSYCHROMETRIC CHART NO. 2

LOW TEMPERATURE

BAROMETRIC PRESSURE: 29.921 INCHES OF MERCURY

SEA LEVEL



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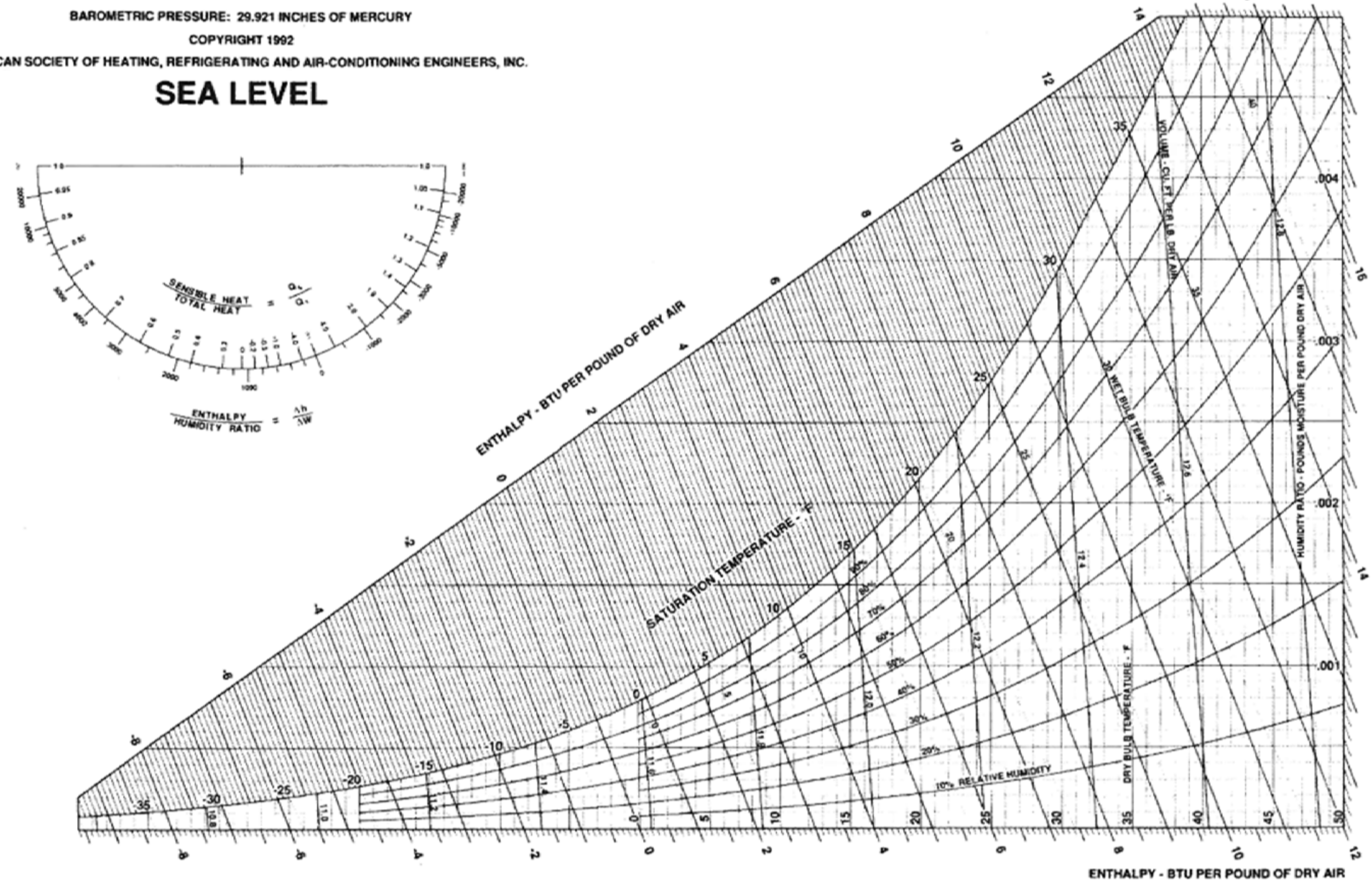

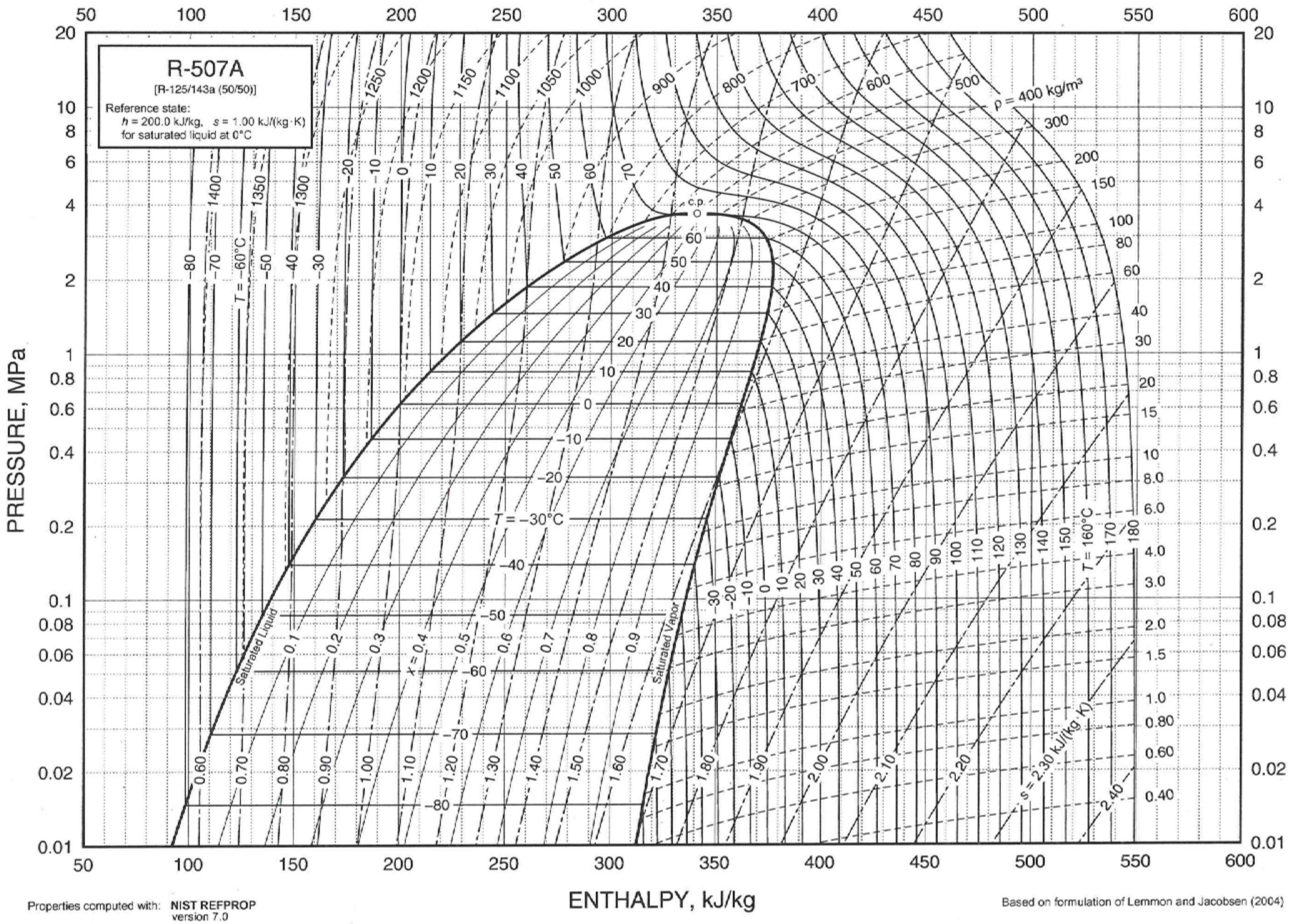

Fig. 15 Pressure-Enthalpy Diagram for Refrigerant 507A

Refrigerant 507A [R-125/143[a] (50/50)] Properties of Saturated Liquid and Saturated Vapor

Temp.,* °C	Pres-sure,** MPa	Density, kg/m³ Liquid	Volume, m³/kg Vapor	Enthalpy, kJ/kg Liquid	Enthalpy, kJ/kg Vapor	Entropy, kJ/(kg·K) Liquid	Entropy, kJ/(kg·K) Vapor	Specific Heat c_p, kJ/(kg·K) Liquid	Specific Heat c_p, kJ/(kg·K) Vapor	c_p/c_v Vapor	Velocity of Sound, m/s Liquid	Velocity of Sound, m/s Vapor	Viscosity, μPa·s Liquid	Viscosity, μPa·s Vapor	Thermal Cond., mW/(m·K) Liquid	Thermal Cond., mW/(m·K) Vapor	Surface Tension, mN/m	Temp.,* °C
−100	0.00295	1476.9	4.92920	74.41	303.90	0.4323	1.7579	1.219	0.618	1.164	1046	129.6	—	—	124.6	5.77	18.35	−100
−95	0.00458	1461.7	3.25360	80.48	306.85	0.4669	1.7377	1.210	0.631	1.162	1000	131.2	784.2	7.29	121.7	6.06	17.88	−95
−90	0.00693	1446.8	2.20850	86.51	309.83	0.5003	1.7197	1.205	0.644	1.161	960	132.6	701.5	7.49	118.8	6.36	17.41	−90
−85	0.01019	1431.9	1.53750	92.53	312.83	0.5327	1.7036	1.203	0.658	1.159	925	134.0	631.9	7.68	116.1	6.67	16.92	−85
−80	0.01464	1417.1	1.09510	98.54	315.85	0.5642	1.6893	1.203	0.672	1.159	892	135.4	572.7	7.88	113.4	6.99	16.43	−80
−75	0.02058	1402.3	0.79638	104.57	318.88	0.5950	1.6766	1.205	0.686	1.158	862	136.6	521.7	8.07	110.8	7.31	15.92	−75
−70	0.02836	1387.4	0.59012	110.60	321.92	0.6250	1.6652	1.208	0.701	1.158	833	137.8	477.4	8.27	108.2	7.63	15.40	−70
−65	0.03837	1372.5	0.44482	116.66	324.96	0.6545	1.6552	1.213	0.716	1.159	806	138.9	438.5	8.46	105.7	7.96	14.88	−65
−60	0.05105	1357.4	0.34056	122.74	328.00	0.6833	1.6463	1.220	0.732	1.160	779	139.8	404.3	8.65	103.2	8.30	14.34	−60
−55	0.06688	1342.3	0.26444	128.87	331.03	0.7116	1.6384	1.227	0.749	1.161	754	140.7	373.8	8.84	100.8	8.65	13.80	−55
−50	0.08638	1326.9	0.20801	135.03	334.05	0.7395	1.6314	1.235	0.766	1.164	729	141.4	346.5	9.02	98.4	9.00	13.24	−50
−48	0.09533	1320.7	0.18960	137.51	335.25	0.7505	1.6288	1.239	0.773	1.165	719	141.6	336.4	9.10	97.4	9.14	13.02	−48
−46.74[b]	0.10132	1316.8	0.17902	139.07	336.01	0.7574	1.6273	1.241	0.777	1.166	713	141.8	330.2	9.15	96.8	9.23	12.88	−46.74
−46	0.10499	1314.5	0.17313	139.99	336.45	0.7615	1.6264	1.243	0.780	1.166	709	141.9	326.7	9.17	96.5	9.28	12.80	−46
−44	0.11541	1308.2	0.15836	142.48	337.65	0.7724	1.6241	1.247	0.787	1.167	699	142.1	317.4	9.25	95.5	9.42	12.57	−44
−42	0.12662	1301.9	0.14510	144.99	338.84	0.7832	1.6219	1.251	0.795	1.169	690	142.3	308.4	9.32	94.6	9.57	12.34	−42
−40	0.13867	1295.6	0.13317	147.49	340.03	0.7940	1.6198	1.255	0.803	1.170	680	142.5	299.8	9.40	93.7	9.71	12.12	−40
−38	0.15159	1289.2	0.12240	150.01	341.21	0.8047	1.6178	1.259	0.810	1.172	670	142.6	291.4	9.47	92.7	9.86	11.89	−38
−36	0.16542	1282.8	0.11268	152.54	342.38	0.8153	1.6159	1.264	0.818	1.174	661	142.7	283.4	9.55	91.8	10.01	11.66	−36
−34	0.18022	1276.3	0.10388	155.08	343.55	0.8260	1.6141	1.269	0.826	1.176	651	142.8	275.7	9.62	90.9	10.16	11.42	−34
−32	0.19602	1269.7	0.09590	157.63	344.72	0.8365	1.6123	1.274	0.835	1.178	642	142.9	268.3	9.70	90.0	10.31	11.19	−32
−30	0.21287	1263.2	0.08865	160.18	345.88	0.8470	1.6107	1.279	0.843	1.180	632	142.9	261.1	9.77	89.1	10.46	10.96	−30
−28	0.23081	1256.5	0.08205	162.75	347.03	0.8575	1.6092	1.284	0.852	1.183	622	143.0	254.1	9.85	88.2	10.61	10.72	−28
−26	0.24989	1249.8	0.07604	165.33	348.17	0.8679	1.6077	1.289	0.861	1.186	613	143.0	247.4	9.93	87.3	10.77	10.49	−26
−24	0.27016	1243.1	0.07055	167.92	349.30	0.8783	1.6063	1.295	0.870	1.188	603	142.9	240.9	10.00	86.5	10.93	10.25	−24
−22	0.29167	1236.3	0.06553	170.52	350.43	0.8886	1.6049	1.301	0.879	1.191	594	142.9	234.5	10.08	85.6	11.08	10.02	−22
−20	0.31446	1229.4	0.06094	173.13	351.54	0.8989	1.6037	1.307	0.888	1.195	584	142.8	228.4	10.15	84.7	11.24	9.78	−20
−18	0.33858	1222.5	0.05673	175.76	352.65	0.9091	1.6024	1.313	0.898	1.198	575	142.7	222.5	10.23	83.8	11.40	9.54	−18
−16	0.36408	1215.4	0.05286	178.39	353.75	0.9193	1.6013	1.319	0.908	1.202	566	142.5	216.8	10.31	83.0	11.56	9.30	−16
−14	0.39102	1208.4	0.04931	181.04	354.83	0.9295	1.6001	1.326	0.918	1.206	556	142.3	211.2	10.39	82.1	11.73	9.06	−14
−12	0.41945	1201.2	0.04603	183.71	355.91	0.9397	1.5991	1.333	0.929	1.210	547	142.1	205.7	10.47	81.2	11.89	8.82	−12
−10	0.44941	1193.9	0.04301	186.39	356.97	0.9498	1.5980	1.340	0.940	1.214	537	141.9	200.5	10.55	80.4	12.06	8.58	−10
−8	0.48096	1186.6	0.04023	189.08	358.02	0.9599	1.5971	1.348	0.951	1.219	528	141.6	195.3	10.63	79.5	12.23	8.34	−8
−6	0.51416	1179.2	0.03765	191.78	359.06	0.9699	1.5961	1.355	0.962	1.224	518	141.3	190.3	10.71	78.7	12.41	8.10	−6
−4	0.54906	1171.7	0.03527	194.51	360.08	0.9800	1.5952	1.363	0.974	1.230	508	141.0	185.5	10.79	77.8	12.58	7.86	−4
−2	0.58571	1164.0	0.03306	197.25	361.08	0.9900	1.5943	1.372	0.987	1.236	499	140.6	180.7	10.88	77.0	12.76	7.62	−2
0	0.62417	1156.3	0.03101	200.00	362.07	1.0000	1.5934	1.381	0.999	1.242	489	140.2	176.1	10.97	76.2	12.96	7.37	0
2	0.66450	1148.5	0.02910	202.77	363.05	1.0100	1.5925	1.390	1.012	1.249	480	139.8	171.6	11.05	75.3	13.16	7.13	2
4	0.70676	1140.5	0.02733	205.56	364.00	1.0199	1.5917	1.399	1.026	1.256	470	139.3	167.2	11.14	74.5	13.36	6.89	4
6	0.75099	1132.4	0.02568	208.37	364.94	1.0299	1.5908	1.410	1.040	1.264	460	138.8	162.9	11.23	73.7	13.57	6.65	6
8	0.79728	1124.2	0.02415	211.20	365.85	1.0398	1.5900	1.420	1.055	1.272	451	138.2	158.7	11.33	72.8	13.79	6.41	8
10	0.84566	1115.9	0.02271	214.04	366.75	1.0498	1.5891	1.431	1.071	1.282	441	137.6	154.5	11.43	72.0	14.01	6.17	10
12	0.89622	1107.4	0.02138	216.91	367.61	1.0597	1.5883	1.443	1.088	1.291	431	137.0	150.5	11.52	71.2	14.24	5.93	12
14	0.94900	1098.7	0.02012	219.80	368.46	1.0696	1.5874	1.455	1.105	1.302	422	136.3	146.6	11.63	70.4	14.49	5.69	14
16	1.00410	1089.9	0.01895	222.71	369.28	1.0796	1.5865	1.468	1.124	1.314	412	135.6	142.7	11.73	69.6	14.75	5.45	16
18	1.06150	1080.9	0.01785	225.65	370.07	1.0895	1.5856	1.482	1.144	1.327	402	134.9	138.9	11.86	68.8	15.01	5.21	18
20	1.12140	1071.7	0.01683	228.61	370.83	1.0995	1.5846	1.497	1.165	1.341	392	134.1	135.1	11.97	67.9	15.29	4.97	20
22	1.18370	1062.4	0.01586	231.60	371.55	1.1094	1.5836	1.513	1.188	1.356	382	133.2	131.5	12.09	67.1	15.58	4.74	22
24	1.24860	1052.8	0.01495	234.61	372.25	1.1194	1.5826	1.530	1.212	1.372	372	132.3	127.9	12.22	66.3	15.89	4.50	24
26	1.31610	1043.0	0.01410	237.66	372.91	1.1294	1.5815	1.548	1.239	1.391	362	131.4	124.3	12.35	65.5	16.21	4.27	26
28	1.38640	1032.9	0.01329	240.73	373.52	1.1394	1.5804	1.568	1.268	1.411	352	130.4	120.8	12.48	64.7	16.54	4.04	28
30	1.45940	1022.6	0.01253	243.84	374.10	1.1495	1.5792	1.589	1.299	1.433	341	129.3	117.4	12.62	63.9	16.90	3.81	30
32	1.53520	1011.9	0.01182	246.98	374.63	1.1595	1.5779	1.612	1.333	1.458	331	128.2	114.0	12.77	63.1	17.28	3.58	32
34	1.61400	1001.0	0.01114	250.16	375.11	1.1697	1.5765	1.637	1.371	1.485	321	127.1	110.6	12.93	62.2	17.68	3.35	34
36	1.69580	989.7	0.01050	253.39	375.54	1.1799	1.5750	1.664	1.413	1.516	310	125.9	107.3	13.10	61.4	18.12	3.12	36
38	1.78070	978.1	0.00989	256.65	375.91	1.1901	1.5734	1.695	1.459	1.551	300	124.6	104.0	13.28	60.6	18.58	2.90	38
40	1.86880	966.0	0.00932	259.96	376.22	1.2004	1.5717	1.729	1.511	1.591	289	123.2	100.7	13.47	59.8	19.09	2.68	40
42	1.96020	953.5	0.00877	263.33	376.46	1.2108	1.5698	1.767	1.570	1.636	278	121.8	97.5	13.68	59.0	19.63	2.47	42
44	2.05490	940.5	0.00825	266.74	376.61	1.2213	1.5678	1.811	1.638	1.689	267	120.4	94.3	13.90	58.1	20.23	2.25	44
46	2.15310	926.9	0.00776	270.23	376.68	1.2320	1.5655	1.860	1.716	1.750	256	118.8	91.0	14.14	57.3	20.89	2.04	46
48	2.25480	912.7	0.00728	273.78	376.66	1.2427	1.5631	1.918	1.807	1.823	245	117.2	87.8	14.41	56.5	21.62	1.83	48
50	2.36030	897.7	0.00683	277.41	376.52	1.2536	1.5603	1.985	1.915	1.910	233	115.5	84.6	14.70	55.7	22.43	1.63	50
55	2.64090	856.2	0.00578	286.91	375.54	1.2818	1.5519	2.225	2.304	2.228	203	110.8	76.4	15.59	53.6	24.98	1.15	55
60	2.94760	806.1	0.00480	297.28	373.26	1.3120	1.5401	2.677	3.060	2.855	171	105.5	67.7	16.86	51.7	28.77	0.70	60
65	3.28380	739.1	0.00384	309.30	368.44	1.3465	1.5215	3.940	5.190	4.625	135	99.3	57.9	18.93	50.7	35.54	0.31	65
70	3.65570	599.6	0.00260	328.32	353.47	1.4007	1.4740	31.960	44.630	36.780	92	90.7	42.0	25.07	63.2	67.27	0.02	70
70.62[c]	3.70500	490.8	0.00204	340.45	340.45	1.4358	1.4358	∞	∞	∞	0	0.0	—	—	—	—	0.00	70.62

*Temperatures on ITS-90 scale

**Small deviations from azeotropic behavior occur at some conditions; tabulated pressures are average of bubble and dew-point pressures

[b]Normal boiling point

[c]Critical point