UNIVERSITY OF ABERDEEN SESSION 2014–2015

Degree Examination in EG3521 Engineering Thermodynamics

0^{th} May 2015 00.00–00.00

Notes: (i) *Candidates ARE permitted to use the approved calculator.*

(ii) *Candidates ARE permitted to use steam tables, which will be provided.*

(iii) *Candidates ARE permitted to use refrigerant tables, which will be provided.*

(iv) *Candidates ARE permitted to use psychrometric chart, which will be provided.*

(v) *Data sheets are attached to the paper.*

PLEASE NOTE THE FOLLOWING

(i) You **must not** have in your possession any material other than that expressly permitted in the rules appropriate to this examination. Where this is permitted, such material **must not** be amended, annotated or modified in any way.

(ii) You **must not** have in your possession any material that could be determined as giving you an advantage in the examination.

(iii) You **must not** attempt to communicate with any candidate during the exam, either orally or by passing written material, or by showing material to another candidate, nor must you attempt to view another candidate's work.

Failure to comply with the above will be regarded as cheating and may lead to disciplinary action as indicated in the Academic Quality Handbook (`www.abdn.ac.uk/registry/quality/appendix7x1.pdf`) **Section 4.14 and 5.**

Candidates must attempt *all* questions.

Question 1

(a) The volume ratios of compression and expansion for a diesel engine are 15.3 and 7.5, respectively. The pressure and temperature at the beginning of the compression are 1 bar and 27 °C. Assume that the volume at the end of the isentropic compression is 1 m^3, determine:

(i) Mean effective pressure $\left(\mathrm{MEP} = \dfrac{\mathrm{W_{net}}}{\mathrm{V_{max}} - \mathrm{V_{min}}}\right)$; [7 marks]

(ii) Cycle efficiency $\left(\eta_{\mathrm{Diesel}} = \dfrac{\mathrm{W_{net}}}{\text{Heat Supplied}}\right)$. [3 marks]

(b) In an ideal air-standard Brayton cycle, air enters the compressor at 0.1 MPa and 15°C and leaves at 1 MPa. Assuming that the maximum temperature of the cycle is 1100°C:

(i) Sketch Pv (pressure × specific volume) and Ts (temperature × specific entropy) diagrams for the cycle, numbering each stage; [2 marks]

(ii) Calculate the temperature of the fluid leaving the compressor and the turbine; [2 marks]

(iii) Determine the efficiency of the cycle $\left(\eta_{\mathrm{Brayton}} = \dfrac{\mathrm{W_{net}}}{\text{Heat Supplied}}\right)$; [2 marks]

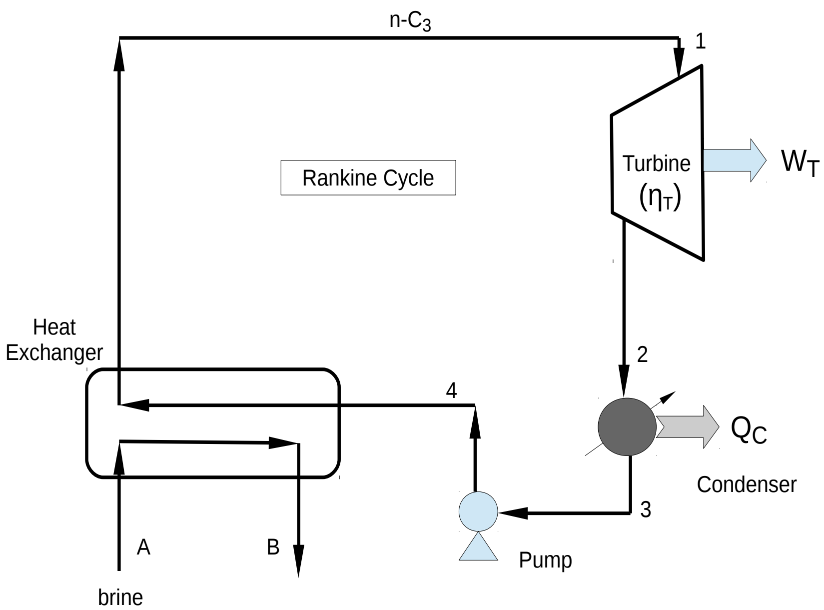
(iv) For the efficiency of the compressor and the turbine of 80% and 85%, respectively, and the pressure drop between the compressor and the turbine of 15 kPa, calculate the work in the compressor and turbine, and the efficiency of the cycle. [4 marks]

Assume that air behaves as an ideal gas with the following properties: MW = 29 g.mol^{-1}, C_p = 1.005 kJ.(kg.K)$^{-1}$ and C_v = 0.718 kJ.(kg.K)$^{-1}$, where MW is the molar mass and C_p and C_v are the heat capacities at constant pressure and volume, respectively. Also, given the following relations for isentropic operations:

$$TV^{\gamma-1} = \text{constant}, \quad TP^{\frac{1-\gamma}{\gamma}} = \text{constant and} \quad PV^{\gamma} = \text{constant}, \quad \text{with } \gamma = \frac{C_p}{C_v}$$

Question 2

(a) A geothermal power station operating with Rankine cycle uses propane (n-C_3) as working fluid to produce power (W_T) in a turbine with efficiency (η_T) of 90%. Propane is vaporised by geothermal water (i.e., brine, $A - B$ in the diagram) at 90°C. After condensed, propane is driven to a heat exchanger and the cycle continues. The mass flow rate of propane ($\dot{m}_{C3}$) is 250 kg.s^{-1} and the heat capacity at constant pressure (C_p) of brine is 3565.5 J.(kg.K)$^{-1}$. Conditions for propane and brine flows are described in the Table below.



Stage	P (bar)	T (^{o}C)	State	Quality	h (kJ.kg^{-1})	s (kJ.(kg.K)$^{-1}$)
1	40	100	(a)	–	(b)	(c)
2	10	–	–	(d)	(e)	(f)
3	–	–	(g)	–	(h)	(i)
4	(j)	–	(k)	–	(l)	–
A	–	90	–	–	–	–
B	–	30	–	–	–	–

Table 1: *Conditions of propane and brine in the cycle.*

(i) In this Table, determine *(a)-(l)*. [6 marks]

(ii) Calculate the power produced by the turbine (W_T) and the heat extracted in the condenser (Q_C) in *MW*. [2 marks]

(iii) Calculate the mass flow rate of brine (A-B) in $kg.s^{-1}$. [2 marks]

(iv) Sketch the Ts (temperature $\times$ specific entropy) diagram for the process indicating the liquid and vapour saturated lines and each stage of the n-C_3 Rankine cycle. [3 marks]

To solve this problem, you should assume that the saturated liquid streams are incompressible, and therefore $dh = vdP$ (where h, v and P are specific enthalpy, volume and pressure, respectively). Quality of the vapour is expressed as

$$x_j = \frac{\Psi_j - \Psi_f}{\Psi_g - \Psi_f} \quad \text{with } \Psi = \{h, s\},$$

where s is the entropy. Efficiency of the turbine (η_{Turbine}) is given by,

$$\eta_{\text{Turbine}} = \frac{h_2 - h_1}{h_{2s} - h_1}$$

where h_{2s} is the enthalpy of stream 2 assuming ideal turbine performance (i.e., reversible expansion).

(b) Air contained in a piston-cylinder system undergoes three consecutive processes,

- Process 1–2: Isobaric cooling with P_1=69 kPa and V_1=0.11 m^3;
- Process 2–3: Isochoric heating with P_3=345 kPa;
- Process 3–1: Polytropic expansion, with $PV = constant$.

(i) Calculate V_2 (in m^3). [2 marks]

(ii) Calculate the work (in kJ) for each process. [3 marks]

(iii) Sketch the PV (pressure $\times$ volume) diagram for these processes. [2 marks]

Question 3

(a) The energy conservation equation for a steady flow device with one inlet and one outlet can be written in the form:

$$\dot{Q} - \dot{W}_s = \dot{m}\left(c_p T_{\text{outlet}} + \frac{u^2_{\text{outlet}}}{2}\right) - \dot{m}\left(c_p T_{\text{inlet}} + \frac{u^2_{\text{inlet}}}{2}\right).$$

(i) Explain what the fluxes on the right-hand side of this equation represent. [2 marks]

(ii) What assumptions are required to derive this equation? [4 marks]

(b) The equation given above is valid for steady flow devices with one inlet and one outlet. Under the same modelling assumptions, state a modified version of this formula that is valid for steady flow devices with one inlet (whose properties are labelled 1) and two outlets (labelled 2 and 3). Derive an equation that represents steady mass conservation in this case. [4 marks]

(c) Gas in a steady flow device with a circular inlet and two circular outlets does shaft work at a rate of 400 kW. The remaining known inlet and outlet properties are:

Property	Inlet 1	Outlet 2	Outlet 3	Units
Diameter, d	0.05	0.2	0.5	m^2
Volume flux, q	1.8	0.5	20	m^3/s
Temperature, T	80	70	30	°C
Pressure, p	200		110	kPa

If the gas behaves like an ideal gas with a gas specific gas constant $R = 250\,\text{J/(kg.K)}$ and specific heat capacity $c_p = 1000$ J/(kg.K), then:

(i) Calculate the fluid velocity through each inlet and outlet; [3 marks]

(ii) Calculate the gas pressure at outlet 2; [5 marks]

(iii) Determine whether the steady flow device heats the gas or whether the gas heats the steady flow device. [2 marks]

Question 4

(a) A change in enthalpy $\mathrm{d}h$, entropy $\mathrm{d}s$ and pressure $\mathrm{d}p$ in an ideal gas are related through

$$\mathrm{d}h = T\mathrm{d}s + V\mathrm{d}p,$$

where T is the absolute temperature and V is the specific volume.

Show that the change in entropy between the inlet and outlet of a compressor is given by

$$s_{\text{outlet}} - s_{\text{inlet}} = c_p \ln\left(\frac{T_{\text{outlet}}}{T_{\text{inlet}}}\right) - R\ln\left(\frac{p_{\text{outlet}}}{p_{\text{inlet}}}\right).$$

Here c_p is the specific heat capacity at constant pressure and R is the specific gas constant, which can both be assumed to be constant. [6 marks]

(b) If the flow through the compressor is isentropic, then show that

$$\frac{T_{\text{outlet}}}{T_{\text{inlet}}} = \left(\frac{p_{\text{outlet}}}{p_{\text{inlet}}}\right)^{1-1/\gamma},$$

where γ is the ratio of the specific heat capacities. [4 marks]

(c) An ideal gas with $R = 260\,\mathrm{J/(kg\,K)}$ and $c_p = 900\,\mathrm{J/(kg\,K)}$ flows through a well designed compressor in which the steady flow energy equation is given by

$$\dot{W}_s = \dot{m}\left(h_{\text{inlet}} - h_{\text{outlet}}\right).$$

The compressor is doing work on the gas at a rate of 500 kW, while the mass flux through the compressor is 4 kg/s. If the compressor has an inlet with pressure $p_{\text{inlet}} = 100\,\mathrm{kPa}$ and temperature $T_{\text{inlet}} = 25°\mathrm{C}$, and an outlet with pressure $p_{\text{outlet}} = 350\,\mathrm{kPa}$, then:

(i) Calculate the actual gas temperature at the outlet. [3 marks]

(ii) Determine the isentropic efficiency of the compressor. [7 marks]

Question 5

An air stream with relative humidity of 0.01 kg water/kg dry air passes through a duct at the rate of 1.2 kg s^{-1}. In the duct the air is first heated from 5°C to 20°C by heating coils and then humidified via the injection of hot steam. Air leaves the device at 25°C with a relative humidity of 60%. The air pressure is 101.325 kPa throughout.

(a) Determine the rate of heat addition in the heating section. [5 marks]

(b) Determine the specific humidity of the air after the humidifying section. [2 marks]

(c) Determine the mass flow rate of steam required in the humidifying section. [5 marks]

(d) Explain why adding steam may be beneficial in this process. [2 marks]

(e) Sketch and identify the evolution of the different stages of this process on rough axes of a psychrometric chart. [6 marks]

You may assume that $c_p = 1005$ J/(kg K), $R_a = 287$ J/(kg K), while the enthalpy of saturated water vapour is 2510.1 kJ/kg at 5°C and 2537.4 kJ/kg at 20°C.

END OF PAPER

Appendix A: Physical Constants and Conversion Factors

PHYSICAL CONSTANTS

Avogadro's number, $N_A = 6.023 \times 10^{26}$ molecules/kgmole
Boltzmann's constant, $k = 1.381 \times 10^{-23}$ J/(molecule·K)
Electron charge, $e = 1.602 \times 10^{-19}$C
Electron mass, $m_e = 9.110 \times 10^{-31}$ kg
Faraday's constant, F = 96,487 kC/kgmole electrons = 96,487 kJ/(V·kgmole electrons)
Gravitational acceleration (standard), $g = 32.174$ ft/s^2 = 9.807 m/s^2
Gravitational constant, $k_G = 6.67 \times 10^{-11}$ m^3/(kg·s^2)
Newton's second law constant, $g_c = 32.174$ lbm·ft/(lbf·s^2) = 1.0 kg·m/(N·s^2)
Planck's constant, $\hbar = 6.626 \times 10^{-34}$ J·s/molecule
Stefan-Boltzmann constant, $\sigma = 0.1714 \times 10^{-8}$ Btu/(h·ft^2·R^4) = 5.670×10^{-8} W/(m^2·k^4)
Universal gas constant $\Re$ = 1545.35 ft·lbf/(lbmole·R) = 8314.3 J/(kgmole·K)
= 8.3143 kJ/(kgmole·K) = 1.9858 Btu/(lbmole·R)
= 1.9858 kcal/(kgmole·K) = 1.9858 cal/(gmole·K)
= 0.08314 bar·m^3/(kgmole·K) = 82.05 L·atm/(kgmole·K)
Velocity of light in a vacuum, $c = 9.836 \times 10^8$ ft/s = 2.998×10^8 m/s

UNIT DEFINITIONS

1 coulomb (C) = 1 A·s	1 ohm (Ω) = 1 V/A
1 dyne = 1 g·cm/s^2	1 pascal (Pa) = 1 N/m^2
1 erg = 1 dyne·cm	1 poundal = 1 lbm·ft/s^2
1 farad (F) = 1 C/V	1 siemens (S) = 1 A/V
1 henry (H) = 1 Wb/A	1 slug = 1 lbf·s^2/ft
1 hertz (Hz) = 1 cycle/s	1 tesla (T) = 1 Wb/m^2
1 joule (J) = 1 N·m	1 volt (V) = 1 W/A
1 lumen = 1 candela·steradian	1 watt (W) = 1 J/s
1 lux = 1 lumen/m^2	1 weber (Wb) = 1 V·s
1 newton (N) = 1 kg·m/s^2	

CONVERSION FACTORS

Length	**Energy**
1 m = 3.2808 ft = 39.37 in = 10^2 cm = 10^{10} Å	1 J = 1 N·m = 1 kg·m^2/s^2 = 9.479 × 10^{-4} Btu
1 cm = 0.0328 ft = 0.394 in = 10^{-2} m = 10^8 Å	1 kJ = 1000 J = 0.9479 Btu = 238.9 cal
1 mm = 10^{-3} m = 10^{-1} cm	1 Btu = 1055.0 J = 1.055 kJ = 778.16 ft·lbf = 252 cal
1 km = 1000 m = 0.6215 miles = 3281 ft	1 cal = 4.186 J = 3.968 × 10^{-3} Btu
1 in = 2.540 cm = 0.0254 m	1 Cal (in food value) = 1 kcal = 4186 J = 3.968 Btu
1 ft = 12 in = 0.3048 m	1 erg = 1 dyne·cm = 1 g·cm^2/s^2 = 10^{-7} J
1 mile = 5280 ft = 1609.36 m = 1.609 km	1 eV = 1.602 × 10^{-19} J

(*Continued*)

CONVERSION FACTORS *(Continued)*

Area

1 m^2 = $10^4 cm^2$ = 10.76 ft^2 = 1550 in^2

1 ft^2 = 144 in^2 = 0.0929 m^2 = 929.05 cm^2

1 cm^2 = 10^{-4} m^2 = 1.0764 × 10^{-3} ft^2 = 0.155 in^2

1 in^2 = 6.944 × 10^{-3} ft^2 = 6.4516 × 10^{-4} m^2 = 6.4516 cm^2

Volume

1 m^3 = 35.313 ft^3 = 6.1023 × 10^4 in^3 = 1000 L = 264.171 gal

1 L = $10^{-3} m^3$ = 0.0353 ft^3 = 61.03 in^3 = 0.2642 gal

1 gal = 231 in^3 = 0.13368 ft^3 = 3.785 × 10^{-3} m^3

1 ft^3 = 1728 in^3 = 28.3168 L = 0.02832 m^3 = 7.4805 gal

1 in^3 = 16.387 cm^3 = 1.6387 × 10^{-5} m^3 = 4.329 × 10^{-3} gal

Mass

1 kg = 1000 g = 2.2046 lbm = 0.0685 slug

1 lbm = 453.6 g = 0.4536 kg = 3.108 × 10^{-2} slug

1 slug = 32.174 lbm = 1.459 × 10^4 g = 14.594 kg

Force

1 N = 10^5 dyne = 1 kg·m/s^2 = 0.225 lbf

1 lbf = 4.448 N = 32.174 poundals

1 poundal = 0.138 N = 3.108 × 10^{-2} lbf

Power

1 W = 1 J/s = 1 kg·m^2/s^3 = 3.412 Btu/h = 1.3405 × 10^{-3} hp

1 kW = 1000 W = 3412 Btu/h = 737.3 ft·lbf/s = 1.3405 hp

1 Btu/h = 0.293 W = 0.2161 ft·lbf/s = 3.9293 × 10^{-4} hp

1 hp = 550 ft·lbf/s = 33000 ft·lbf/min = 2545 Btu/h = 746 W

Pressure

1 Pa = 1 N/m^2 = 1 kg/(m·s^2) = 1.4504 × 10^{-4} lbf/in^2

1 lbf/in^2 = 6894.76 Pa = 0.068 atm = 2.036 in Hg

1 atm = 14.696 lbf/in^2 = 1.01325 × 10^5 Pa

= 101.325 kPa = 760 mm Hg

1 bar = 10^5 Pa = 0.987 atm = 14.504 lbf/in^2

1 dyne/cm^2 = 0.1 Pa = 10^{-6} bar = 145.04 × 10^{-7} lbf/in^2

1 in Hg = 3376.8 Pa = 0.491 lbf/in^2

1 in H_2O = 248.8 Pa = 0.0361 lbf/in^2

MISCELLANEOUS UNIT CONVERSIONS

Specific Heat Units

1 Btu/(lbm·°F) = 1 Btu/(lbm·R)

1 kJ/(kg·K) = 0.23884 Btu/(lbm·R) = 185.8 ft·lbf/(lbm·R)

1 Btu/(lbm·R) = 778.16 ft·lbf/(lbm·R) = 4.186 kJ/(kg·K)

Energy Density Units

1 kJ/kg = 1000 m^2/s^2 = 0.4299 Btu/lbm

1 Btu/lbm = 2.326 kJ/kg = 2326 m^2/s^2

Energy Flux

1 W/m^2 = 0.317 Btu/(h·ft^2)

1 Btu/(h·ft^2) = 3.154 W/m^2

Heat Transfer Coefficient

1 W/(m^2·K) = 0.1761 Btu/(h·ft^2·R)

1 Btu/(h·ft^2·R) = 5.679 W/(m^2·K)

Thermal Conductivity

1 W/(m·K) = 0.5778 Btu/(h·ft·R)

1 Btu/(h·ft·R) = 1.731 W/(m·K)

Temperature

$T(°F) = \frac{9}{5}T(°C) + 32 = T(R) - 459.67$

$T(°C) = \frac{5}{9}[T(°F) - 32] = T(K) - 273.15$

$T(R) = \frac{9}{5}T(K) = (1.8)T(K) = T(°F) + 459.67$

$T(K) = \frac{5}{9}T(R) = T(R)/1.8 = T(°C) + 273.15$

Density

1 lbm/ft^3 = 16.0187 kg/m^3

1 kg/m^3 = 0.062427 lbm/ft^3 = 10^{-3} g/cm^3

1 g/cm^3 = 1 kg/L = 62.4 lbm/ft^3 = 10^3 kg/m^3

Viscosity

1 Pa·s = 1 N·s/m^2 = 1 kg/(m·s) = 10 poise

1 poise = 1 dyne·s/cm^2 = 1 g/(cm·s) = 0.1 Pa·s

1 poise = 2.09 × 10^{-3} lbf·s/ft^2 = 6.72 × 10^{-2} lbm/(ft·s)

1 centipoise = 0.01 poise = 10^{-3} Pa·s

1 lbf·s/ft^2 = 1 slug/(ft·s) = 47.9 Pa·s = 479 poise

1 stoke = 1 cm^2/s = 10^{-4} m^2/s = 1.076 × 10^{-3} ft^2/s

1 centistoke = 0.01 stoke = 10^{-6} m^2/s = 1.076 × 10^{-5} ft^2/s

1 m^2/s = 10^4 stoke = 10^6 centistoke = 10.76 ft^2/s

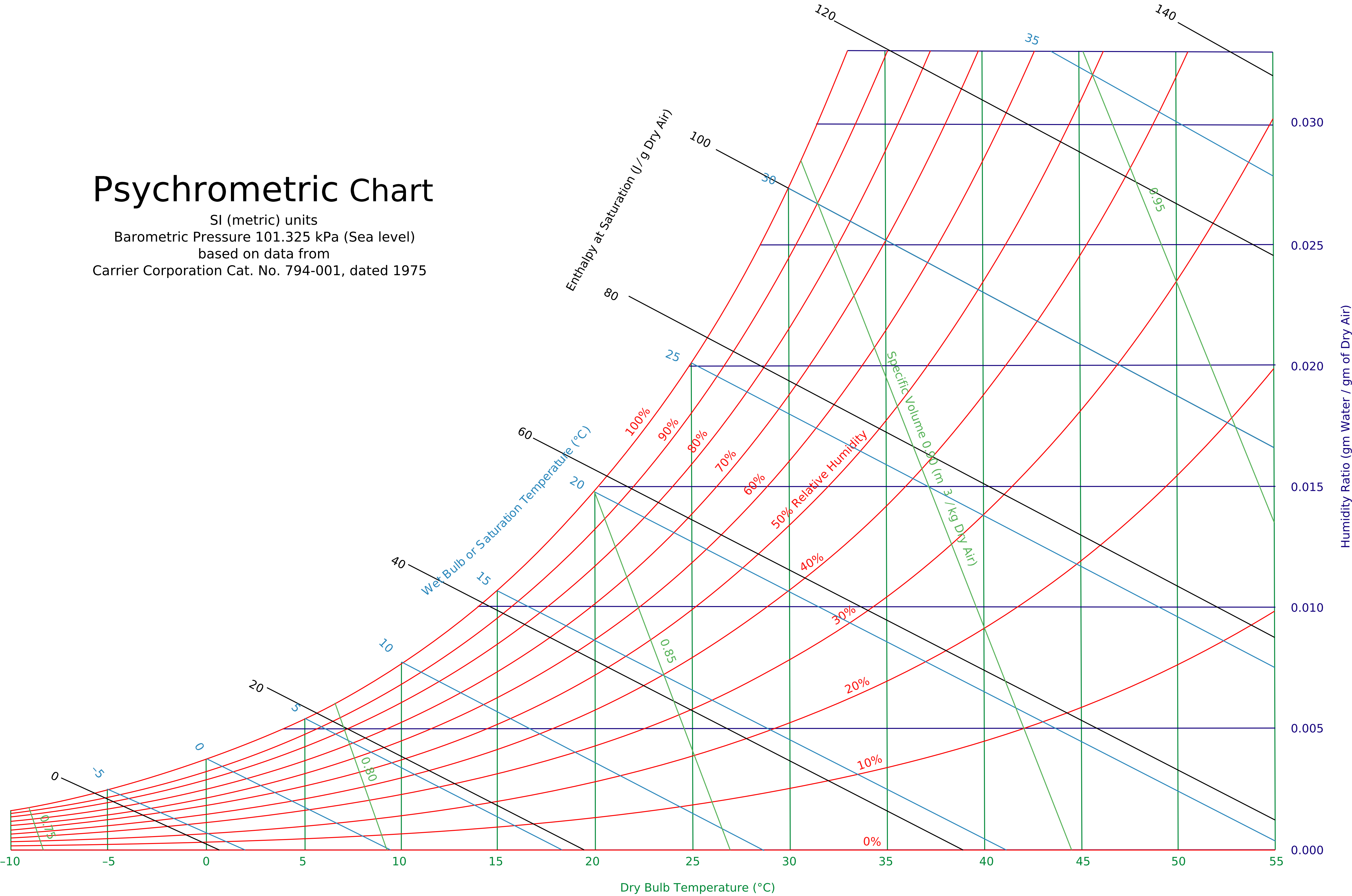

Psychrometric Chart
SI (metric) units
Barometric Pressure 101.325 kPa (Sea level)
based on data from
Carrier Corporation Cat. No. 794-001, dated 1975
Enthalpy at Saturation (J / g Dry Air)
0
20
40
60
80
100
120
140
Wet Bulb or Saturation Temperature (°C)
-5
0
5
10
15
20
25
30
35
100%
90%
80%
70%
60%
50% Relative Humidity
40%
30%
20%
10%
0%
Specific Volume 0.90 (m 3 /kg Dry Air)
0.75
0.80
0.85
0.95
Humidity Ratio (gm Water / gm of Dry Air)
0.000
0.005
0.010
0.015
0.020
0.025
0.030
-10
-5
0
5
10
15
20
25
30
35
40
45
50
55
Dry Bulb Temperature (°C)

TABLE A-16 Properties of Saturated Propane (Liquid–Vapor): Temperature Table

Temp. °C	Press. bar	Specific Volume m^3/kg Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Internal Energy kJ/kg Sat. Liquid u_f	Sat. Vapor u_g	Enthalpy kJ/kg Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Entropy kJ/kg · K Sat. Liquid s_f	Sat. Vapor s_g	Temp. °C
−100	0.02888	1.553	11.27	−128.4	319.5	−128.4	480.4	352.0	−0.634	2.140	−100
−90	0.06426	1.578	5.345	−107.8	329.3	−107.8	471.4	363.6	−0.519	2.055	−90
−80	0.1301	1.605	2.774	−87.0	339.3	−87.0	462.4	375.4	−0.408	1.986	−80
−70	0.2434	1.633	1.551	−65.8	349.5	−65.8	453.1	387.3	−0.301	1.929	−70
−60	0.4261	1.663	0.9234	−44.4	359.9	−44.3	443.5	399.2	−0.198	1.883	−60
−50	0.7046	1.694	0.5793	−22.5	370.4	−22.4	433.6	411.2	−0.098	1.845	−50
−40	1.110	1.728	0.3798	−0.2	381.0	0.0	423.2	423.2	0.000	1.815	−40
−30	1.677	1.763	0.2585	22.6	391.6	22.9	412.1	435.0	0.096	1.791	−30
−20	2.444	1.802	0.1815	45.9	402.4	46.3	400.5	446.8	0.190	1.772	−20
−10	3.451	1.844	0.1309	69.8	413.2	70.4	388.0	458.4	0.282	1.757	−10
0	4.743	1.890	0.09653	94.2	423.8	95.1	374.5	469.6	0.374	1.745	0
4	5.349	1.910	0.08591	104.2	428.1	105.3	368.8	474.1	0.410	1.741	4
8	6.011	1.931	0.07666	114.3	432.3	115.5	362.9	478.4	0.446	1.737	8
12	6.732	1.952	0.06858	124.6	436.5	125.9	356.8	482.7	0.482	1.734	12
16	7.515	1.975	0.06149	135.0	440.7	136.4	350.5	486.9	0.519	1.731	16
20	8.362	1.999	0.05525	145.4	444.8	147.1	343.9	491.0	0.555	1.728	20
24	9.278	2.024	0.04973	156.1	448.9	158.0	337.0	495.0	0.591	1.725	24
28	10.27	2.050	0.04483	166.9	452.9	169.0	329.9	498.9	0.627	1.722	28
32	11.33	2.078	0.04048	177.8	456.7	180.2	322.4	502.6	0.663	1.720	32
36	12.47	2.108	0.03659	188.9	460.6	191.6	314.6	506.2	0.699	1.717	36
40	13.69	2.140	0.03310	200.2	464.3	203.1	306.5	509.6	0.736	1.715	40
44	15.00	2.174	0.02997	211.7	467.9	214.9	298.0	512.9	0.772	1.712	44
48	16.40	2.211	0.02714	223.4	471.4	227.0	288.9	515.9	0.809	1.709	48
52	17.89	2.250	0.02459	235.3	474.6	239.3	279.3	518.6	0.846	1.705	52
56	19.47	2.293	0.02227	247.4	477.7	251.9	269.2	521.1	0.884	1.701	56
60	21.16	2.340	0.02015	259.8	480.6	264.8	258.4	523.2	0.921	1.697	60
65	23.42	2.406	0.01776	275.7	483.6	281.4	243.8	525.2	0.969	1.690	65
70	25.86	2.483	0.01560	292.3	486.1	298.7	227.7	526.4	1.018	1.682	70
75	28.49	2.573	0.01363	309.5	487.8	316.8	209.8	526.6	1.069	1.671	75
80	31.31	2.683	0.01182	327.6	488.2	336.0	189.2	525.2	1.122	1.657	80
85	34.36	2.827	0.01011	347.2	486.9	356.9	164.7	521.6	1.178	1.638	85
90	37.64	3.038	0.008415	369.4	482.2	380.8	133.1	513.9	1.242	1.608	90
95	41.19	3.488	0.006395	399.8	467.4	414.2	79.5	493.7	1.330	1.546	95
96.7	42.48	4.535	0.004535	434.9	434.9	454.2	0.0	457.2	1.437	1.437	96.7

Source: Tables A-16 through A-18 are calculated based on B. A. Younglove and J. F. Ely, "Thermophysical Properties of Fluids. II. Methane, Ethane, Propane, Isobutane and Normal Butane," *J. Phys. Chem. Ref. Data,* Vol. 16, No. 4, 1987, pp. 577–598.

TABLE A-17 Properties of Saturated Propane (Liquid–Vapor): Pressure Table

		Specific Volume m^3/kg		Internal Energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/kg · K		
Press. bar	Temp. °C	Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Sat. Liquid u_f	Sat. Vapor u_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Sat. Liquid s_f	Sat. Vapor s_g	Press. bar
0.05	−93.28	1.570	6.752	−114.6	326.0	−114.6	474.4	359.8	−0.556	2.081	0.05
0.10	−83.87	1.594	3.542	−95.1	335.4	−95.1	465.9	370.8	−0.450	2.011	0.10
0.25	−69.55	1.634	1.513	−64.9	350.0	−64.9	452.7	387.8	−0.297	1.927	0.25
0.50	−56.93	1.672	0.7962	−37.7	363.1	−37.6	440.5	402.9	−0.167	1.871	0.50
0.75	−48.68	1.698	0.5467	−19.6	371.8	−19.5	432.3	412.8	−0.085	1.841	0.75
1.00	−42.38	1.719	0.4185	−5.6	378.5	−5.4	425.7	420.3	−0.023	1.822	1.00
2.00	−25.43	1.781	0.2192	33.1	396.6	33.5	406.9	440.4	0.139	1.782	2.00
3.00	−14.16	1.826	0.1496	59.8	408.7	60.3	393.3	453.6	0.244	1.762	3.00
4.00	−5.46	1.865	0.1137	80.8	418.0	81.5	382.0	463.5	0.324	1.751	4.00
5.00	1.74	1.899	0.09172	98.6	425.7	99.5	372.1	471.6	0.389	1.743	5.00
6.00	7.93	1.931	0.07680	114.2	432.2	115.3	363.0	478.3	0.446	1.737	6.00
7.00	13.41	1.960	0.06598	128.2	438.0	129.6	354.6	484.2	0.495	1.733	7.00
8.00	18.33	1.989	0.05776	141.0	443.1	142.6	346.7	489.3	0.540	1.729	8.00
9.00	22.82	2.016	0.05129	152.9	447.6	154.7	339.1	493.8	0.580	1.726	9.00
10.00	26.95	2.043	0.04606	164.0	451.8	166.1	331.8	497.9	0.618	1.723	10.00
11.00	30.80	2.070	0.04174	174.5	455.6	176.8	324.7	501.5	0.652	1.721	11.00
12.00	34.39	2.096	0.03810	184.4	459.1	187.0	317.8	504.8	0.685	1.718	12.00
13.00	37.77	2.122	0.03499	193.9	462.2	196.7	311.0	507.7	0.716	1.716	13.00
14.00	40.97	2.148	0.03231	203.0	465.2	206.0	304.4	510.4	0.745	1.714	14.00
15.00	44.01	2.174	0.02997	211.7	467.9	215.0	297.9	512.9	0.772	1.712	15.00
16.00	46.89	2.200	0.02790	220.1	470.4	223.6	291.4	515.0	0.799	1.710	16.00
17.00	49.65	2.227	0.02606	228.3	472.7	232.0	285.0	517.0	0.824	1.707	17.00
18.00	52.30	2.253	0.02441	236.2	474.9	240.2	278.6	518.8	0.849	1.705	18.00
19.00	54.83	2.280	0.02292	243.8	476.9	248.2	272.2	520.4	0.873	1.703	19.00
20.00	57.27	2.308	0.02157	251.3	478.7	255.9	265.9	521.8	0.896	1.700	20.00
22.00	61.90	2.364	0.01921	265.8	481.7	271.0	253.0	524.0	0.939	1.695	22.00
24.00	66.21	2.424	0.01721	279.7	484.3	285.5	240.1	525.6	0.981	1.688	24.00
26.00	70.27	2.487	0.01549	293.1	486.2	299.6	226.9	526.5	1.021	1.681	26.00
28.00	74.10	2.555	0.01398	306.2	487.5	313.4	213.2	526.6	1.060	1.673	28.00
30.00	77.72	2.630	0.01263	319.2	488.1	327.1	198.9	526.0	1.097	1.664	30.00
35.00	86.01	2.862	0.009771	351.4	486.3	361.4	159.1	520.5	1.190	1.633	35.00
40.00	93.38	3.279	0.007151	387.9	474.7	401.0	102.3	503.3	1.295	1.574	40.00
42.48	96.70	4.535	0.004535	434.9	434.9	454.2	0.0	454.2	1.437	1.437	42.48

TABLE A-18 Properties of Superheated Propane

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	p = 0.05 bar = 0.005 MPa (T_{sat} = −93.28°C)				p = 0.1 bar = 0.01 MPa (T_{sat} = −83.87°C)			
Sat.	6.752	326.0	359.8	2.081	3.542	367.3	370.8	2.011
−90	6.877	329.4	363.8	2.103				
−80	7.258	339.8	376.1	2.169	3.617	339.5	375.7	2.037
−70	7.639	350.6	388.8	2.233	3.808	350.3	388.4	2.101
−60	8.018	361.8	401.9	2.296	3.999	361.5	401.5	2.164
−50	8.397	373.3	415.3	2.357	4.190	373.1	415.0	2.226
−40	8.776	385.1	429.0	2.418	4.380	385.0	428.8	2.286
−30	9.155	397.4	443.2	2.477	4.570	397.3	443.0	2.346
−20	9.533	410.1	457.8	2.536	4.760	410.0	457.6	2.405
−10	9.911	423.2	472.8	2.594	4.950	423.1	472.6	2.463
0	10.29	436.8	488.2	2.652	5.139	436.7	488.1	2.520
10	10.67	450.8	504.1	2.709	5.329	450.6	503.9	2.578
20	11.05	270.6	520.4	2.765	5.518	465.1	520.3	2.634
	p = 0.5 bar = 0.05 MPa (T_{sat} = −56.93°C)				p = 1.0 bar = 0.1 MPa (T_{sat} = −42.38°C)			
Sat.	0.796	363.1	402.9	1.871	0.4185	378.5	420.3	1.822
−50	0.824	371.3	412.5	1.914				
−40	0.863	383.4	426.6	1.976	0.4234	381.5	423.8	1.837
−30	0.903	396.0	441.1	2.037	0.4439	394.2	438.6	1.899
−20	0.942	408.8	455.9	2.096	0.4641	407.3	453.7	1.960
−10	0.981	422.1	471.1	2.155	0.4842	420.7	469.1	2.019
0	1.019	435.8	486.7	2.213	0.5040	434.4	484.8	2.078
10	1.058	449.8	502.7	2.271	0.5238	448.6	501.0	2.136
20	1.096	464.3	519.1	2.328	0.5434	463.3	517.6	2.194
30	1.135	479.2	535.9	2.384	0.5629	478.2	534.5	2.251
40	1.173	494.6	553.2	2.440	0.5824	493.7	551.9	2.307
50	1.211	510.4	570.9	2.496	0.6018	509.5	569.7	2.363
60	1.249	526.7	589.1	2.551	0.6211	525.8	587.9	2.419
	p = 2.0 bar = 0.2 MPa (T_{sat} = −25.43°C)				p = 3.0 bar = 0.3 MPa (T_{sat} = −14.16°C)			
Sat.	0.2192	396.6	440.4	1.782	0.1496	408.7	453.6	1.762
−20	0.2251	404.0	449.0	1.816				
−10	0.2358	417.7	464.9	1.877	0.1527	414.7	460.5	1.789
0	0.2463	431.8	481.1	1.938	0.1602	429.0	477.1	1.851
10	0.2566	446.3	497.6	1.997	0.1674	443.8	494.0	1.912
20	0.2669	461.1	514.5	2.056	0.1746	458.8	511.2	1.971
30	0.2770	476.3	531.7	2.113	0.1816	474.2	528.7	2.030
40	0.2871	491.9	549.3	2.170	0.1885	490.1	546.6	2.088
50	0.2970	507.9	567.3	2.227	0.1954	506.2	564.8	2.145
60	0.3070	524.3	585.7	2.283	0.2022	522.7	583.4	2.202
70	0.3169	541.1	604.5	2.339	0.2090	539.6	602.3	2.258
80	0.3267	558.4	623.7	2.394	0.2157	557.0	621.7	2.314
90	0.3365	576.1	643.4	2.449	0.2223	574.8	641.5	2.369

TABLE A-18 *(Continued)*

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	p = 4.0 bar = 0.4 MPa (T_{sat} = −5.46°C)				p = 5.0 bar = 0.5 MPa (T_{sat} = 1.74°C)			
Sat.	0.1137	418.0	463.5	1.751	0.09172	425.7	471.6	1.743
0	0.1169	426.1	472.9	1.786				
10	0.1227	441.2	490.3	1.848	0.09577	438.4	486.3	1.796
20	0.1283	456.6	507.9	1.909	0.1005	454.1	504.3	1.858
30	0.1338	472.2	525.7	1.969	0.1051	470.0	522.5	1.919
40	0.1392	488.1	543.8	2.027	0.1096	486.1	540.9	1.979
50	0.1445	504.4	562.2	2.085	0.1140	502.5	559.5	2.038
60	0.1498	521.1	581.0	2.143	0.1183	519.4	578.5	2.095
70	0.1550	538.1	600.1	2.199	0.1226	536.6	597.9	2.153
80	0.1601	555.7	619.7	2.255	0.1268	554.1	617.5	2.209
90	0.1652	573.5	639.6	2.311	0.1310	572.1	637.6	2.265
100	0.1703	591.8	659.9	2.366	0.1351	590.5	658.0	2.321
110	0.1754	610.4	680.6	2.421	0.1392	609.3	678.9	2.376
	p = 6.0 bar = 0.6 MPa (T_{sat} = 7.93°C)				p = 7.0 bar = 0.7 MPa (T_{sat} = 13.41°C)			
Sat.	0.07680	432.2	478.3	1.737	0.06598	438.0	484.2	1.733
10	0.07769	435.6	482.2	1.751				
20	0.08187	451.5	500.6	1.815	0.06847	448.8	496.7	1.776
30	0.08588	467.7	519.2	1.877	0.07210	465.2	515.7	1.840
40	0.08978	484.0	537.9	1.938	0.07558	481.9	534.8	1.901
50	0.09357	500.7	556.8	1.997	0.07896	498.7	554.0	1.962
60	0.09729	517.6	576.0	2.056	0.08225	515.9	573.5	2.021
70	0.1009	535.0	595.5	2.113	0.08547	533.4	593.2	2.079
80	0.1045	552.7	615.4	2.170	0.08863	551.2	613.2	2.137
90	0.1081	570.7	635.6	2.227	0.09175	569.4	633.6	2.194
100	0.1116	589.2	656.2	2.283	0.09482	587.9	654.3	2.250
110	0.1151	608.0	677.1	2.338	0.09786	606.8	675.3	2.306
120	0.1185	627.3	698.4	2.393	0.1009	626.2	696.8	2.361
	p = 8.0 bar = 0.8 MPa (T_{sat} = 18.33°C)				p = 9.0 bar = 0.9 MPa (T_{sat} = 22.82°C)			
Sat.	0.05776	443.1	489.3	1.729	0.05129	447.2	493.8	1.726
20	0.05834	445.9	492.6	1.740				
30	0.06170	462.7	512.1	1.806	0.05355	460.0	508.2	1.774
40	0.06489	479.6	531.5	1.869	0.05653	477.2	528.1	1.839
50	0.06796	496.7	551.1	1.930	0.05938	494.7	548.1	1.901
60	0.07094	514.0	570.8	1.990	0.06213	512.2	568.1	1.962
70	0.07385	531.6	590.7	2.049	0.06479	530.0	588.3	2.022
80	0.07669	549.6	611.0	2.107	0.06738	548.1	608.7	2.081
90	0.07948	567.9	631.5	2.165	0.06992	566.5	629.4	2.138
100	0.08222	586.5	652.3	2.221	0.07241	585.2	650.4	2.195
110	0.08493	605.6	673.5	2.277	0.07487	604.3	671.7	2.252
120	0.08761	625.0	695.1	2.333	0.07729	623.7	693.3	2.307
130	0.09026	644.8	717.0	2.388	0.07969	643.6	715.3	2.363
140	0.09289	665.0	739.3	2.442	0.08206	663.8	737.7	2.418

TABLE A-18 (*Continued*)

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	p = 10.0 bar = 1.0 MPa (T_{sat} = 26.95°C)				p = 12.0 bar = 1.2 MPa (T_{sat} = 34.39°C)			
Sat.	0.04606	451.8	497.9	1.723	0.03810	459.1	504.8	1.718
30	0.04696	457.1	504.1	1.744				
40	0.04980	474.8	524.6	1.810	0.03957	469.4	516.9	1.757
50	0.05248	492.4	544.9	1.874	0.04204	487.8	538.2	1.824
60	0.05505	510.2	565.2	1.936	0.04436	506.1	559.3	1.889
70	0.05752	528.2	585.7	1.997	0.04657	524.4	580.3	1.951
80	0.05992	546.4	606.3	2.056	0.04869	543.1	601.5	2.012
90	0.06226	564.9	627.2	2.114	0.05075	561.8	622.7	2.071
100	0.06456	583.7	648.3	2.172	0.05275	580.9	644.2	2.129
110	0.06681	603.0	669.8	2.228	0.05470	600.4	666.0	2.187
120	0.06903	622.6	691.6	2.284	0.05662	620.1	688.0	2.244
130	0.07122	642.5	713.7	2.340	0.05851	640.1	710.3	2.300
140	0.07338	662.8	736.2	2.395	0.06037	660.6	733.0	2.355
	p = 14.0 bar = 1.4 MPa (T_{sat} = 40.97°C)				p = 16.0 bar = 1.6 MPa (T_{sat} = 46.89°C)			
Sat.	0.03231	465.2	510.4	1.714	0.02790	470.4	515.0	1.710
50	0.03446	482.6	530.8	1.778	0.02861	476.7	522.5	1.733
60	0.03664	501.6	552.9	1.845	0.03075	496.6	545.8	1.804
70	0.03869	520.4	574.6	1.909	0.03270	516.2	568.5	1.871
80	0.04063	539.4	596.3	1.972	0.03453	535.7	590.9	1.935
90	0.04249	558.6	618.1	2.033	0.03626	555.2	613.2	1.997
100	0.04429	577.9	639.9	2.092	0.03792	574.8	635.5	2.058
110	0.04604	597.5	662.0	2.150	0.03952	594.7	657.9	2.117
120	0.04774	617.5	684.3	2.208	0.04107	614.8	680.5	2.176
130	0.04942	637.7	706.9	2.265	0.04259	635.3	703.4	2.233
140	0.05106	658.3	729.8	2.321	0.04407	656.0	726.5	2.290
150	0.05268	679.2	753.0	2.376	0.04553	677.1	749.9	2.346
160	0.05428	700.5	776.5	2.431	0.04696	698.5	773.6	2.401
	p = 18.0 bar = 1.8 MPa (T_{sat} = 52.30°C)				p = 20.0 bar = 2.0 MPa (T_{sat} = 57.27°C)			
Sat.	0.02441	474.9	518.8	1.705	0.02157	478.7	521.8	1.700
60	0.02606	491.1	538.0	1.763	0.02216	484.8	529.1	1.722
70	0.02798	511.4	561.8	1.834	0.02412	506.3	554.5	1.797
80	0.02974	531.6	585.1	1.901	0.02585	527.1	578.8	1.867
90	0.03138	551.5	608.0	1.965	0.02744	547.6	602.5	1.933
100	0.03293	571.5	630.8	2.027	0.02892	568.1	625.9	1.997
110	0.03443	591.7	653.7	2.087	0.03033	588.5	649.2	2.059
120	0.03586	612.1	676.6	2.146	0.03169	609.2	672.6	2.119
130	0.03726	632.7	699.8	2.204	0.03299	630.0	696.0	2.178
140	0.03863	653.6	723.1	2.262	0.03426	651.2	719.7	2.236
150	0.03996	674.8	746.7	2.318	0.03550	672.5	743.5	2.293
160	0.04127	696.3	770.6	2.374	0.03671	694.2	767.6	2.349
170	0.04256	718.2	794.8	2.429	0.03790	716.2	792.0	2.404
180	0.04383	740.4	819.3	2.484	0.03907	738.5	816.6	2.459

Propane

TABLE A-18 (*Continued*)

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg · K	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	p = 22.0 bar = 2.2 MPa (T_{sat} = 61.90°C)				p = 24.0 bar = 2.4 MPa (T_{sat} = 66.21°C)			
Sat.	0.01921	481.8	524.0	1.695	0.01721	484.3	525.6	1.688
70	0.02086	500.5	546.4	1.761	0.01802	493.7	536.9	1.722
80	0.02261	522.4	572.1	1.834	0.01984	517.0	564.6	1.801
90	0.02417	543.5	596.7	1.903	0.02141	539.0	590.4	1.873
100	0.02561	564.5	620.8	1.969	0.02283	560.6	615.4	1.941
110	0.02697	585.3	644.6	2.032	0.02414	581.9	639.8	2.006
120	0.02826	606.2	668.4	2.093	0.02538	603.2	664.1	2.068
130	0.02949	627.3	692.2	2.153	0.02656	624.6	688.3	2.129
140	0.03069	648.6	716.1	2.211	0.02770	646.0	712.5	2.188
150	0.03185	670.1	740.2	2.269	0.02880	667.8	736.9	2.247
160	0.03298	691.9	764.5	2.326	0.02986	689.7	761.4	2.304
170	0.03409	714.1	789.1	2.382	0.03091	711.9	786.1	2.360
180	0.03517	736.5	813.9	2.437	0.03193	734.5	811.1	2.416
	p = 26.0 bar = 2.6 MPa (T_{sat} = 70.27°C)				p = 30.0 bar = 3.0 MPa (T_{sat} = 77.72°C)			
Sat.	0.01549	486.2	526.5	1.681	0.01263	488.2	526.0	1.664
80	0.01742	511.0	556.3	1.767	0.01318	495.4	534.9	1.689
90	0.01903	534.2	583.7	1.844	0.01506	522.8	568.0	1.782
100	0.02045	556.4	609.6	1.914	0.01654	547.2	596.8	1.860
110	0.02174	578.3	634.8	1.981	0.01783	570.4	623.9	1.932
120	0.02294	600.0	659.6	2.045	0.01899	593.0	650.0	1.999
130	0.02408	621.6	684.2	2.106	0.02007	615.4	675.6	2.063
140	0.02516	643.4	708.8	2.167	0.02109	637.7	701.0	2.126
150	0.02621	665.3	733.4	2.226	0.02206	660.1	726.3	2.186
160	0.02723	687.4	758.2	2.283	0.02300	682.6	751.6	2.245
170	0.02821	709.9	783.2	2.340	0.02390	705.4	777.1	2.303
180	0.02918	732.5	808.4	2.397	0.02478	728.3	802.6	2.360
190	0.03012	755.5	833.8	2.452	0.02563	751.5	828.4	2.417
	p = 35.0 bar = 3.5 MPa (T_{sat} = 86.01°C)				p = 40.0 bar = 4.0 MPa (T_{sat} = 93.38°C)			
Sat.	0.00977	486.3	520.5	1.633	0.00715	474.7	503.3	1.574
90	0.01086	502.4	540.5	1.688				
100	0.01270	532.9	577.3	1.788	0.00940	512.1	549.7	1.700
110	0.01408	558.9	608.2	1.870	0.01110	544.7	589.1	1.804
120	0.01526	583.4	636.8	1.944	0.01237	572.1	621.6	1.887
130	0.01631	607.0	664.1	2.012	0.01344	597.4	651.2	1.962
140	0.01728	630.2	690.7	2.077	0.01439	621.9	679.5	2.031
150	0.01819	653.3	717.0	2.140	0.01527	645.9	707.0	2.097
160	0.01906	676.4	743.1	2.201	0.01609	669.7	734.1	2.160
170	0.01989	699.6	769.2	2.261	0.01687	693.4	760.9	2.222
180	0.02068	722.9	795.3	2.319	0.01761	717.3	787.7	2.281
190	0.02146	746.5	821.6	2.376	0.01833	741.2	814.5	2.340
200	0.02221	770.3	848.0	2.433	0.01902	765.3	841.4	2.397