SCHOOL OF ENGINEERING

Form to accompany draft examination papers sent to external examiners

Course Code: EG3029

Diet of Examinations: Exam

Materials required to be provided in the examination room when the examination is sat (in addition to the question paper and answer booklets):
None

Are candidates permitted to use approved calculators in the examination?
Yes

Details of materials which candidates are permitted to take into the examination room and use when answering the examination paper (in addition to writing and drawing instruments, and approved calculators where permitted):
None

Details of any departures from the agreed syllabus for this course:
N/A

Any information which the examiners feel should be communicated to the external examiners:
N/A

The examination paper has been prepared and scrutinised following current procedures:

Jefferson Gomes	**Course Organiser**
Panagiotis Kechagiopoulos	**Scrutineer**
20/10/2014	**Date**

UNIVERSITY OF ABERDEEN SESSION 2014–2015

Degree Examination in EG3029

0th December 2014 00.00–00.00

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

(ii) Candidates ARE permitted to use tables of thermodynamic properties of fluids, which will be provided.

(iii) 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

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

- Process 1–2: Compression at constant pressure from P_1=69 kPa and V_1=0.11 m^3 to State 2;
- Process 2–3: Constant volume heating to state 3, with P_3=345 kPa;
- Process 3–1: Expansion to the initial state, during which the pressure-volume relationship is $PV = \textit{constant}$.

(a) Calculate V_2 $\left(\text{in } m^3\right)$. [4 marks]

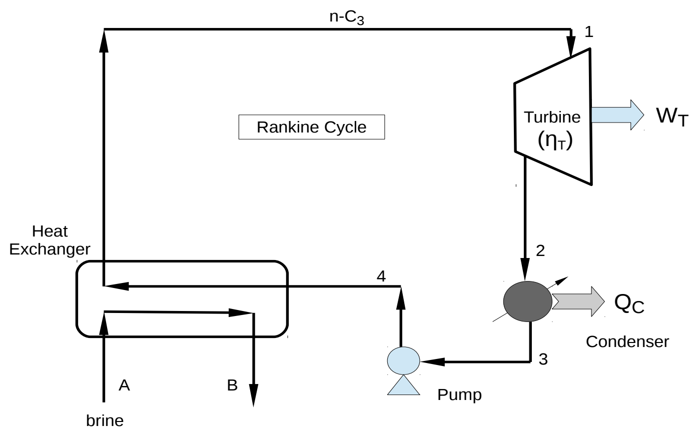
(b) Calculate the work (in J) for each process. [6 marks]

(c) Sketch the PV diagram for these processes. [4 marks]

(ii) A closed system with 0.09 kg of air undergoes a polytropic process from $P_1 = 138$ kPa, V_1=0.72 $m^3.kg^{-1}$ to a final state where $P_2 = 552$ kPa, $V_2 = 0.25$ $m^3.kg^{-1}$. Determine the work (in J) required for this compression. [6 marks]

Question 2

A geothermal power station (Rankine cycle) uses propane (n-C_3) as working fluid to produce power (W_T) in a turbine (isentropic expansion) with efficiency (η_T) of 90%. n-C_3 is vaporised by geothermal water (brine, $A - B$) at 90°C. After condensed, n-C_3 is driven to a heat exchanger (with thermal efficiency of 68%) and the cycle continues. The mass flow rate of n-C_3 ($\dot{m}_{C3}$) is 250 kg.s^{-1} and the heat capacity (C_p) of brine is 3565.5 J.(kg.K)$^{-1}$. Conditions for n-C_3 and brine flows are described in Table below.



Stage	**P (bar)**	**T (^{o}C)**	**State**	**H (kJ.kg^{-1})**	**S (kJ.(kg.K)$^{-1}$)**
1	16	50	**(a)**	**(b)**	**(c)**
2	6	–	wet vapour	**(d)**	–
3	6		sat. liquid	**(e)**	–
4	16		**(f)**	**(g)**	–
A	–	90	–	–	–
B	–	30	–	–	–

(a) In this Table, determine *(a)-(g)*. [7 marks]

(b) Calculate the power produced by the turbine (W_T) and the heat extracted in the condenser (Q_C) in *MW*. [4 marks]

(c) Assuming that the heat exchanger has an efficiency of 68%, calculate the mass flow rate of brine in $kg.s^{-1}$. [6 marks]

(d) Sketch the temperature × entropy (TS) 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 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}) and the heat exchanger (η_{HE}) are given by,

$$\eta_{\text{Turbine}} = \frac{H_2 - H_1}{H_{2s} - H_1} \quad \text{and} \quad \eta_{\text{HE}} = \frac{\dot{Q}_{C3}}{\dot{Q}_{gf}}$$

where H_{2s} is the enthalpy of stream 2 assuming ideal turbine performance (i.e., reversible expansion). $\dot{Q}_{C3}$ and $\dot{Q}_{gf}$ are the heat associated with the n-C_3 and brine streams, respectively, at the heat exchanger.

Question 3

(i) Develop expressions for the volume expansivity, $\beta = \dfrac{1}{V}\left(\dfrac{\partial V}{\partial T}\right)_P$, and isothermal compressibility, $\kappa = -\dfrac{1}{V}\left(\dfrac{\partial V}{\partial P}\right)_T$, for the following equations of state,

(a) ideal gas [4 marks]

(b) $V = \dfrac{RT}{P} + b$ [4 marks]

(ii) Calculate the compressibility factor (Z) of 1.35×10^{-3} m^3.gmol^{-1} of chloroform at 450 K and 20 bar using the Soave-Redlich-Kwong equation of state. Properties of chloroform are: T_c = 537 K, P_c = 5328.68 kPa and ω =0.218 (accentric factor). In your iterative calculations, use $PV = ZRT$ as an initial guess of Z, and stop at the second iteration (Z_2). [12 marks]

Question 4

The excess molar volume of a solution of ethanol (1) and methyl-buthyl ether (2) at 298.15 K is given by the following expression:

$$\overline{V}^{\mathrm{E}} = x_1 x_2 \left[-1.026 + 0.22\left(x_1 - x_2\right)\right]$$

Given that $\overline{V}_1 = 58.63\ \mathrm{cm}^3.\mathrm{gmol}^{-1}$ and $\overline{V}_2 = 118.46\ \mathrm{cm}^3.\mathrm{gmol}^{-1}$ $\left(\overline{V}_i\right.$ is the molar volume of component i), what is the volume of the solution when 750 cm^3 of pure ethanol is mixed with 1500 cm^3 of methyl-buthyl ether at 298.15 K? What would be the volume if the solution was ideal? [20 marks]

Question 5

A mixture of 2 kg of H_2 and 4 kg of N_2 was compressed in a piston-cylinder in a polytropic process with $n = 1.2$. During the compression, the temperature increased from 22 to 150°C. Determine the heat transfer (in kJ) and the entropy change (in kJ/K) of the process. The entropy change is expressed as,

$$\Delta S = m_T \left[\overline{C}_v \ln \frac{T_2}{T_1} + \frac{R}{\overline{MW}} \ln \frac{V_2}{V_1} \right]$$

where m_T is the total mass of the gaseous mixture, $\overline{MW}$ and $\overline{C}_v$ are the averaged molecular weight and heat capacity at constant volume of the mixture. For this range of temperature, you should assume constant heat capacity at constant volume (C_v) of 0.745 and 10.32 kJ.(kg.K)$^{-1}$, for N_2 and H_2, respectively. Molecular weight of H_2: 2.016 kg.kgmol^{-1}, N_2: 28.01 kg.kgmol^{-1}. [20 marks]

- Generic cubic equation of state:

$$Z = 1 + \beta - q\beta \frac{Z - \beta}{(Z + \varepsilon\beta)(Z + \sigma\beta)} \quad \text{(vapour and vapour-like roots)}$$

$$Z = 1 + \beta + (Z + \epsilon\beta)(Z + \sigma\beta)\left(\frac{1 + \beta - Z}{q\beta}\right) \quad \text{(liquid and liquid-like roots)}$$

$$\text{with } \beta = \Omega\frac{P_r}{T_r} \quad \text{and} \quad q = \frac{\Psi\alpha(T_r)}{\Omega T_r}$$

$$\alpha_{\text{SRK}} = \left[1 + \left(0.480 + 1.574\omega - 0.176\omega^2\right)\left(1 - \sqrt{T_r}\right)\right]^2$$

$$\alpha_{\text{PR}} = \left[1 + \left(0.37464 + 1.54226\omega - 0.26992\omega^2\right)\left(1 - \sqrt{T_r}\right)\right]^2$$

EOS	α	σ	ε	Ω	Ψ
vdW	1	0	0	1/8	27/64
RK	$T_r^{-1/2}$	1	0	0.08664	0.42748
SRK	α_{SRK}	1	0	0.08664	0.42748
PR	α_{PR}	$1+\sqrt{2}$	$1-\sqrt{2}$	0.07780	0.45724

- Newton-Raphson (root-finder) method: $X_i = X_{i-1} - \dfrac{\mathcal{F}(X_{i-1})}{d\mathcal{F}/dX\,(X_{i-1})}$

- Fundamental thermodynamic equations:

$$dU = dQ + dW; \quad dH = dU + d(PV); \quad dA = dU - d(TS); \quad dG = dH - d(TS)$$

$$dU = TdS - PdV; \quad dH = TdS + VdP; \quad dA = -SdT - PdV; \quad dG = -SdT + VdP$$

$$dH = C_p dT + \left[V - T\left(\frac{\partial V}{\partial T}\right)_P\right]dP; \quad dS = C_p\frac{dT}{T} - \left(\frac{\partial V}{\partial T}\right)_P dP$$

$$dU = C_v dT + \left[T\left(\frac{\partial P}{\partial T}\right)_V - P\right]dV; \quad dS = C_v\frac{dT}{T} - \left(\frac{\partial P}{\partial T}\right)_V dV$$

- Polytropic Relations:

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} ; TV^{\gamma-1} = \text{ const}; \; TP^{\frac{1-\gamma}{\gamma}} = \text{ const}; \; PV^{\gamma} = \text{ const}$$

- Raoult's Law:

$$y_i P = x_i P_i^{\text{sat}} \quad \text{and} \quad y_i P = x_i \gamma_i P_i^{\text{sat}} \quad \text{with } i = 1, 2, \cdots N$$

- Henry's Law:

$$x_i \mathcal{H}_i = y_i P \quad \text{with } i = 1, 2, \cdots N$$

- Antoine Equation:

$$\log_{10} P^\star = A - \frac{B}{T + C} \quad \text{with P}^\star \text{ in mm-Hg and T in °C}$$

- Solutions:

$$M^{\text{E}} = M - \sum_{i=1}^{N} x_i M_i; \; \overline{M}_1 = M + x_2\frac{dM}{dx_1}; \; \overline{M}_2 = M - x_1\frac{dM}{dx_1}$$

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), $g = 32.174\ \text{ft/s}^2 = 9.807\ \text{m/s}^2$
Gravitational constant, $k_G = 6.67 \times 10^{-11}\ \text{m}^3/(\text{kg}\cdot\text{s}^2)$
Newton's second law constant, $g_c = 32.174\ \text{lbm}\cdot\text{ft}/(\text{lbf}\cdot\text{s}^2) = 1.0\ \text{kg}\cdot\text{m}/(\text{N}\cdot\text{s}^2)$
Planck's constant, $\hbar = 6.626 \times 10^{-34}$ J·s/molecule
Stefan-Boltzmann constant, $\sigma = 0.1714 \times 10^{-8}\ \text{Btu}/(\text{h}\cdot\text{ft}^2\cdot\text{R}^4) = 5.670 \times 10^{-8}\ \text{W}/(\text{m}^2\cdot\text{k}^4)$
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)
= $0.08314\ \text{bar}\cdot\text{m}^3/(\text{kgmole}\cdot\text{K})$ = 82.05 L·atm/(kgmole·K)
Velocity of light in a vacuum, $c = 9.836 \times 10^8\ \text{ft/s} = 2.998 \times 10^8\ \text{m/s}$

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

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

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

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

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

Volume

$1\ m^3 = 35.313\ ft^3 = 6.1023 \times 10^4\ in^3 = 1000\ L = 264.171\ gal$

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

$1\ gal = 231\ in^3 = 0.13368\ ft^3 = 3.785 \times 10^{-3}\ m^3$

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

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

Mass

1 kg = 1000 g = 2.2046 lbm = 0.0685 slug

$1\ lbm = 453.6\ g = 0.4536\ kg = 3.108 \times 10^{-2}\ slug$

$1\ slug = 32.174\ lbm = 1.459 \times 10^4\ g = 14.594\ kg$

Force

$1\ N = 10^5\ dyne = 1\ kg{\cdot}m/s^2 = 0.225\ lbf$

1 lbf = 4.448 N = 32.174 poundals

$1\ poundal = 0.138\ N = 3.108 \times 10^{-2}\ lbf$

Power

$1\ W = 1\ J/s = 1\ kg{\cdot}m^2/s^3 = 3.412\ Btu/h = 1.3405 \times 10^{-3}\ hp$

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

$1\ Btu/h = 0.293\ W = 0.2161\ ft{\cdot}lbf/s = 3.9293 \times 10^{-4}\ hp$

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

Pressure

$1\ Pa = 1\ N/m^2 = 1\ kg/(m{\cdot}s^2) = 1.4504 \times 10^{-4}\ lbf/in^2$

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

$1\ atm = 14.696\ lbf/in^2 = 1.01325 \times 10^5\ Pa$

= 101.325 kPa = 760 mm Hg

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

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

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

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

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

$1\ W/m^2 = 0.317\ Btu/(h{\cdot}ft^2)$

$1\ Btu/(h{\cdot}ft^2) = 3.154\ W/m^2$

Heat Transfer Coefficient

$1\ W/(m^2{\cdot}K) = 0.1761\ Btu/(h{\cdot}ft^2{\cdot}R)$

$1\ Btu/(h{\cdot}ft^2{\cdot}R) = 5.679\ W/(m^2{\cdot}K)$

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

$1\ Pa{\cdot}s = 1\ N{\cdot}s/m^2 = 1\ kg/(m{\cdot}s) = 10\ poise$

$1\ poise = 1\ dyne{\cdot}s/cm^2 = 1\ g/(cm{\cdot}s) = 0.1\ Pa{\cdot}s$

$1\ poise = 2.09 \times 10^{-3}\ lbf{\cdot}s/ft^2 = 6.72 \times 10^{-2}\ lbm/(ft{\cdot}s)$

$1\ centipoise = 0.01\ poise = 10^{-3}\ Pa{\cdot}s$

$1\ lbf{\cdot}s/ft^2 = 1\ slug/(ft{\cdot}s) = 47.9\ Pa{\cdot}s = 479\ poise$

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

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

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

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

		Specific Volume m³/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 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 = 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

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 = 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