

UNIVERSITY OF ABERDEEN    SESSION 2012–2013

Degree Examination in EG3539 Thermodynamics

16<sup>th</sup> August 2013

09.00–12.00

- Notes:*
- (i) Candidates ARE permitted to use an approved calculator.*
  - (ii) Candidates ARE permitted to use refrigerant tables, 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](http://www.abdn.ac.uk/registry/quality/appendix7x1.pdf)) Section 4.14 and 5.

Candidates must attempt *all* questions.

**Question 1**

An engine operates in a *dual cycle* with compression ( $r_c$ ) and expansion ( $r_e$ ) ratios of 9 and 5, respectively. The initial pressure and temperature of the air are 1 bar and 30°C. The heat liberated at constant pressure is twice the heat liberated at constant volume, i.e.,

$$C_p (T_4 - T_3) = 2C_v (T_3 - T_2).$$

The isentropic expansion and compression strokes follow  $PV^n = \text{constant}$ , with  $n = 1.25$ . The cylinder bore (diameter) is of 250 mm and the stroke length is of 400 mm.

- (a) Calculate pressures and temperatures at all strokes and fill up the table below,

Stroke	P (bar)	T (K)
1	1.0	303.15
2		
3		
4		
5		

[8 Marks]

- (b) Sketch the  $P$ - $v$  diagram for this cycle, indicating the swept ( $V_s$ ) and TDC ( $V_c$ ) volumes.

[2 Marks]

- (c) Calculate the Mean Effective Pressure (MEP) of the cycle (in bar) using the following expression:

$$MEP = \frac{1}{r_c - 1} \left[ P_3 (\rho - 1) + \frac{P_4 \rho - P_5 r_c}{n - 1} - \frac{P_2 - P_1 r_c}{n - 1} \right]$$

[2 Marks]

- (d) Calculate *work done per cycle* (in kJ) and the *heat supplied per cycle* (in kJ), given by

$$W_{\text{cycle}} = MEP \times V_s \quad \text{and} \quad Q_{\text{cycle}} = mQ_s = m[C_p(T_3 - T_2) + C_p(T_4 - T_3)]$$

$$\text{Given: } V_1 = V_s + V_c = \frac{r_c}{r_c - 1} V_s$$

[2 Marks]

- (e) Sketch  $T$ - $S$  and  $P$ - $V$  diagrams for the Otto and Diesel cycles.

[6 Marks]

Also given:

$$C_p = 1.0 \frac{\text{kJ}}{\text{kg.K}} , \quad C_v = 0.71 \frac{\text{kJ}}{\text{kg.K}} , \quad MW = 29 \frac{\text{g}}{\text{gmol}} \quad (\text{molecular weight}),$$

$$R = 8.3144621 \times 10^{-5} \frac{\text{m}^3 \cdot \text{bar}}{\text{K} \cdot \text{gmol}} \quad (\text{gas constant}), \quad \rho = \frac{r_c}{r_e}$$

**Question 2**

- (a) A biodiesel manufacturing plant takes animal fats as feedstock and also spent cooking oil for refining. The output of the plant is 75000 tonnes per year of biodiesel. Assigning this a calorific value of  $37 \text{ MJ.kg}^{-1}$ , calculate the amount of fossil fuel derived carbon dioxide eliminated by its use in preference to mineral diesel of calorific value  $43 \text{ MJ.kg}^{-1}$ . Given, atomic weights/ $\text{g.mol}^{-1}$ : C: 12 and H: 1.

[8 Marks]

- (b) By what chemical process can the performance of a bio-diesel be improved?

[2 Marks]

- (c) What is one major benefit of having natural gas in its liquefied form?

[2 Marks]

- (d) Natural gas is supplied in liquefied form to a particular terminal as LNG (liquefied natural gas, heat of combustion  $55 \text{ MJ.kg}^{-1}$ ) in a quantity of 1.2 million tonnes per annum where it is converted back to gas and used to generate electricity. At what rate will it so generate if the efficiency is 35%?

[8 Marks]

**Question 3**

- (a) The steady flow energy conservation can be written in the form:

$$\frac{\dot{Q} - \dot{W}_s}{\dot{m}} = \left( h_{out} + \frac{u_{out}^2}{2} + gz_{out} \right) - \left( h_{in} + \frac{u_{in}^2}{2} + gz_{in} \right)$$

- (i) Explain the meaning of the symbols and terms in this equation.

[3 Marks]

- (ii) What assumptions are used to derive this expression?

[3 Marks]

- (b) The equation given above is valid for steady flow devices with one inlet and one outlet. State a modified version of this formula that is valid of steady flow devices with two inlets (whose properties are labelled 1 and 2) and one outlet (labelled 3). Give an equation representing steady mass conservation in this case.

[3 Marks]

- (c) A steady flow device with two inlets and one outlet does work on the fluid at a rate of 80 kW. The remaining known inlet and outlet properties are given by:

Property	Inlet 1	Inlet 2	Outlet 3	Units
Cross-sectional area, $A$	0.03	0.1	0.5	m <sup>2</sup>
Inlet/outlet height, $z$	0.2	1.2	0.5	m
Volume flux, $q$	1.8	0.5	20	m <sup>3</sup> /s
Temperature, $T$	80	70	30	°C
Pressure, $p$	200		110	kPa

Assuming the fluid behaves as an ideal gas with  $R = 0.3$  kJ/(kg.K) and  $C_p = 800$  kJ/(kg.K), calculate:

- (i) The fluid velocity through each inlet and outlet;

[2 Marks]

- (ii) The pressure  $p_2$ ;

[6 Marks]

- (iii) The rate is heat added to gas.

[2 Marks]

- (d) Comment on whether the gas transfers heat to the surroundings or whether the steady flow device heats the gas.

[1 Mark]

**Question 4**

A vapour-compression refrigeration system circulates Refrigerant 134a at a rate of 6 kg/min. The refrigerant enters the compressor at  $-10^{\circ}\text{C}$ , 1.4 bar and exits at 7 bar. The isentropic compressor efficiency is 67%. There are no appreciable pressure drops as the refrigerant flows through the condenser and evaporator. The refrigerant leaves the condenser at 7 bar,  $24^{\circ}\text{C}$ . Ignoring heat transfer between the compressor and its surroundings, determine:

- (a)  $H_i, i \in \{1, 2, 3, 4\}$ ;

[8 Marks]

- (b) Coefficient of performance,  $\beta$ ;

$$\beta = \frac{H_1 - H_4}{H_2 - H_1}$$

[3 Marks]

- (c) Refrigeration capacity,  $\dot{Q}_{\text{in}}$  (in ton),

$$\dot{Q}_{\text{in}} = \dot{m} (H_1 - H_4)$$

[3 Marks]

- (d) Sketch the schematics of the process and  $T$ - $S$  diagram for this cycle.

[6 Marks]

In the expressions above for  $\beta$  and  $\dot{Q}_{\text{in}}$ , assume that subscripts 1, 2, 3 and 4 represent the following flows:

- 1: Evaporator  $\Rightarrow$  Compressor;
- 2: Compressor  $\Rightarrow$  Condenser;
- 3: Condenser  $\Rightarrow$  Expansion Valve and;
- 4: Expansion Valve  $\Rightarrow$  Evaporator.

Also given:  $1 \text{ ton} = 1.4 \times 10^4 \frac{\text{kJ}}{\text{h}}$

**Question 5**

- (a) Define the specific humidity  $\omega$ , the saturation pressure of water vapour  $p_{v,\text{sat}}$ , and relative humidity  $\varphi$ . Assuming that dry air and water vapour behave like ideal gases show that

$$\omega = \frac{R_a \varphi p_{v,\text{sat}}}{R_v (p - \varphi p_{g,v,\text{sat}})},$$

where  $R_a$  and  $R_v$  are the specific gas constants of dry air and water vapour, respectively.

**[5 Marks]**

- (b) Air leaving an air-conditioning system in a building is mixed adiabatically with air from outside in a steady process. If the inlets to the mixing chamber are labelled 1 and 2 and the outlet is labelled 3, then state equations corresponding to the mass conservation of dry air, the mass conservation of water vapour and the conservation of energy. Hence show that

$$\frac{\dot{m}_{a2}}{\dot{m}_{a1}} = \frac{\omega - \omega_1}{\omega_2 - \omega_3} = \frac{h_3 - h_1}{h_2 - h_3}$$

where  $\dot{m}_a$  is a mass flux of dry air and  $h$  is an enthalpy.

**[7 Marks]**

- (c) Saturated air at 16°C leaves the cooling section of an air-conditioning system in a building at a rate of 1 m<sup>3</sup>/s. This air is mixed adiabatically at a constant pressure of 100 kPa, with air from outside that has temperature 30°C and specific humidity 0.0182 kg H<sub>2</sub>O/kg dry air. If the mass flux of dry air after mixing is 1.8 kg/s, then:

- (i) Determine the mass flux through both inlets;

**[3 Marks]**

- (ii) Calculate the specific humidity of the air leaving the cooling section of the air-conditioning system;

**[1 Mark]**

- (iii) Calculate the specific humidity of the mixed air.

**[4 Marks]**

You may assume the saturation pressure of water vapour at 16°C is 1818.747 Pa and that the specific gas constants  $R_a = 287.1 \text{ J/(kg.K)}$  and  $R_v = 461.5 \text{ J/(kg.K)}$ , respectively.

**END OF PAPER**

**TABLE V**  
**Conversion Factors**

**Force**

1 newton	=	1 kg-m/sec <sup>2</sup>
	=	0.012 kgf
1 kgf	=	9.81 N

**Pressure**

1 bar	=	750.06 mm Hg
	=	0.9869 atm
	=	10 <sup>5</sup> N/m <sup>2</sup>
	=	10 <sup>3</sup> kg/m-sec <sup>2</sup>
1 N/m <sup>2</sup>	=	1 pascal
	=	10 <sup>-5</sup> bar
	=	10 <sup>-2</sup> kg/m-sec <sup>2</sup>
1 atm	=	760 mm Hg
	=	1.03 kgf/cm <sup>2</sup> = 1.01325 bar
	=	1.01325 × 10 <sup>5</sup> N/m <sup>2</sup>

**Work, Energy or Heat**

1 joule	=	1 newton metre
	=	1 watt-sec
	=	2.7778 × 10 <sup>-7</sup> kWh
	=	0.239 cal
	=	0.239 × 10 <sup>-3</sup> kcal
1 cal	=	4.184 joule
	=	1.1622 × 10 <sup>-6</sup> kWh
1 kcal	=	4.184 × 10 <sup>3</sup> joule
	=	427 kgfm
	=	1.1622 × 10 <sup>-3</sup> kWh
1 kWh	=	8.6 × 10 <sup>5</sup> cal
	=	860 kcal
	=	3.6 × 10 <sup>6</sup> joule
1 kgfm	=	$\left( \frac{1}{427} \right)$ kcal = 9.81 joules

**Power**

1 watt	=	1 joule/sec = 0.86 kcal/h
1 h.p.	=	75 mkgf/sec = 0.1757 kcal/sec
	=	735.3 watt
1 kW	=	1000 watts
	=	860 kcal/h



**Specific heat**

$$1 \text{ kcal/kg} \cdot ^\circ\text{K} = 4.18 \text{ kJ/kg}\cdot\text{K}$$

**Thermal conductivity**

$$\begin{aligned} 1 \text{ watt/m}\cdot\text{K} &= 0.8598 \text{ kcal/h}\cdot\text{m}\cdot^\circ\text{C} \\ 1 \text{ kcal/h}\cdot\text{m}\cdot^\circ\text{C} &= 1.16123 \text{ watt/m}\cdot\text{K} \\ &= 1.16123 \text{ joules/s}\cdot\text{m}\cdot\text{K} \end{aligned}$$

**Heat transfer co-efficient**

$$\begin{aligned} 1 \text{ watt/m}^2\cdot\text{K} &= 0.86 \text{ kcal/m}^2\cdot\text{h}\cdot^\circ\text{C} \\ 1 \text{ kcal/m}^2\cdot\text{h}\cdot^\circ\text{C} &= 1.163 \text{ watt/m}^2\cdot\text{K} \end{aligned}$$

**IMPORTANT ENGINEERING CONSTANTS AND EXPRESSIONS IN SI UNITS**

	<i>Engineering constants and expressions</i>	<i>M.K.S. system</i>	<i>S.I. units</i>
1.	Value of $g_0$	9.81 kg-m/kgf-sec <sup>2</sup>	1 kg-m/N-sec <sup>2</sup>
2.	Universal gas constant	848 kgf-m/kg mole- $^\circ\text{K}$	$848 \times 9.81 = 8314 \text{ J/kg}\cdot\text{mole}\cdot^\circ\text{K}$ ( $\because 1 \text{ kgf}\cdot\text{m} = 9.81 \text{ joules}$ )
3.	Gas constant (R)	29.27 kgf m/kg- $^\circ\text{K}$ for air	$\frac{8314}{29} = 287 \text{ joules/kg}\cdot\text{K}$ for air
4.	Specific heats (for air)	$c_v = 0.17 \text{ kcal/kg}\cdot^\circ\text{K}$ $c_p = 0.24 \text{ kcal/kg}\cdot^\circ\text{K}$	$c_v = 0.17 \times 4.184 = 0.71128 \text{ kJ/kg}\cdot\text{K}$ $c_p = 0.24 \times 4.184 = 1 \text{ kJ/kg}\cdot\text{K}$
5.	Flow through nozzle-exit velocity ( $C_2$ )	$91.5 \sqrt{U}$ where U is in kcal	$44.7 \sqrt{U}$ where U is in kJ
6.	Refrigeration 1 ton	= 50 kcal/min	= 210 kJ/min
7.	<b>Heat transfer</b> The Stefan Boltzman Law is given by :	$Q = \sigma T^4 \text{ kcal/m}^2\cdot\text{h}$ when $\sigma = 4.9 \times 10^{-8} \text{ kcal/h}\cdot\text{m}^2\cdot^\circ\text{K}^4$	$Q = \sigma T^4 \text{ watts/m}^2\cdot\text{h}$ when $\sigma = 5.67 \times 10^{-8} \text{ W/m}^2\cdot\text{K}^4$

**TABLE A-10** Properties of Saturated Refrigerant 134a (Liquid–Vapor): Temperature Table

Temp. °C	Press. bar	Specific Volume m <sup>3</sup> /kg		Internal Energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/kg · K		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 $s_g$	
–40	0.5164	0.7055	0.3569	–0.04	204.45	0.00	222.88	222.88	0.0000	0.9560	–40
–36	0.6332	0.7113	0.2947	4.68	206.73	4.73	220.67	225.40	0.0201	0.9506	–36
–32	0.7704	0.7172	0.2451	9.47	209.01	9.52	218.37	227.90	0.0401	0.9456	–32
–28	0.9305	0.7233	0.2052	14.31	211.29	14.37	216.01	230.38	0.0600	0.9411	–28
–26	1.0199	0.7265	0.1882	16.75	212.43	16.82	214.80	231.62	0.0699	0.9390	–26
–24	1.1160	0.7296	0.1728	19.21	213.57	19.29	213.57	232.85	0.0798	0.9370	–24
–22	1.2192	0.7328	0.1590	21.68	214.70	21.77	212.32	234.08	0.0897	0.9351	–22
–20	1.3299	0.7361	0.1464	24.17	215.84	24.26	211.05	235.31	0.0996	0.9332	–20
–18	1.4483	0.7395	0.1350	26.67	216.97	26.77	209.76	236.53	0.1094	0.9315	–18
–16	1.5748	0.7428	0.1247	29.18	218.10	29.30	208.45	237.74	0.1192	0.9298	–16
–12	1.8540	0.7498	0.1068	34.25	220.36	34.39	205.77	240.15	0.1388	0.9267	–12
–8	2.1704	0.7569	0.0919	39.38	222.60	39.54	203.00	242.54	0.1583	0.9239	–8
–4	2.5274	0.7644	0.0794	44.56	224.84	44.75	200.15	244.90	0.1777	0.9213	–4
0	2.9282	0.7721	0.0689	49.79	227.06	50.02	197.21	247.23	0.1970	0.9190	0
4	3.3765	0.7801	0.0600	55.08	229.27	55.35	194.19	249.53	0.2162	0.9169	4
8	3.8756	0.7884	0.0525	60.43	231.46	60.73	191.07	251.80	0.2354	0.9150	8
12	4.4294	0.7971	0.0460	65.83	233.63	66.18	187.85	254.03	0.2545	0.9132	12
16	5.0416	0.8062	0.0405	71.29	235.78	71.69	184.52	256.22	0.2735	0.9116	16
20	5.7160	0.8157	0.0358	76.80	237.91	77.26	181.09	258.36	0.2924	0.9102	20
24	6.4566	0.8257	0.0317	82.37	240.01	82.90	177.55	260.45	0.3113	0.9089	24
26	6.8530	0.8309	0.0298	85.18	241.05	85.75	175.73	261.48	0.3208	0.9082	26
28	7.2675	0.8362	0.0281	88.00	242.08	88.61	173.89	262.50	0.3302	0.9076	28
30	7.7006	0.8417	0.0265	90.84	243.10	91.49	172.00	263.50	0.3396	0.9070	30
32	8.1528	0.8473	0.0250	93.70	244.12	94.39	170.09	264.48	0.3490	0.9064	32
34	8.6247	0.8530	0.0236	96.58	245.12	97.31	168.14	265.45	0.3584	0.9058	34
36	9.1168	0.8590	0.0223	99.47	246.11	100.25	166.15	266.40	0.3678	0.9053	36
38	9.6298	0.8651	0.0210	102.38	247.09	103.21	164.12	267.33	0.3772	0.9047	38
40	10.164	0.8714	0.0199	105.30	248.06	106.19	162.05	268.24	0.3866	0.9041	40
42	10.720	0.8780	0.0188	108.25	249.02	109.19	159.94	269.14	0.3960	0.9035	42
44	11.299	0.8847	0.0177	111.22	249.96	112.22	157.79	270.01	0.4054	0.9030	44
48	12.526	0.8989	0.0159	117.22	251.79	118.35	153.33	271.68	0.4243	0.9017	48
52	13.851	0.9142	0.0142	123.31	253.55	124.58	148.66	273.24	0.4432	0.9004	52
56	15.278	0.9308	0.0127	129.51	255.23	130.93	143.75	274.68	0.4622	0.8990	56
60	16.813	0.9488	0.0114	135.82	256.81	137.42	138.57	275.99	0.4814	0.8973	60
70	21.162	1.0027	0.0086	152.22	260.15	154.34	124.08	278.43	0.5302	0.8918	70
80	26.324	1.0766	0.0064	169.88	262.14	172.71	106.41	279.12	0.5814	0.8827	80
90	32.435	1.1949	0.0046	189.82	261.34	193.69	82.63	276.32	0.6380	0.8655	90
100	39.742	1.5443	0.0027	218.60	248.49	224.74	34.40	259.13	0.7196	0.8117	100

Source: Tables A-10 through A-12 are calculated based on equations from D. P. Wilson and R. S. Basu, "Thermodynamic Properties of a New Stratospherically Safe Working Fluid—Refrigerant 134a," *ASHRAE Trans.*, Vol. 94, Pt. 2, 1988, pp. 2095–2118.

**TABLE A-11** Properties of Saturated Refrigerant 134a (Liquid–Vapor): Pressure Table

Press. bar	Temp. °C	Specific Volume m <sup>3</sup> /kg		Internal Energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/kg · K		Press. bar
		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 $s_g$	
0.6	−37.07	0.7097	0.3100	3.41	206.12	3.46	221.27	224.72	0.0147	0.9520	0.6
0.8	−31.21	0.7184	0.2366	10.41	209.46	10.47	217.92	228.39	0.0440	0.9447	0.8
1.0	−26.43	0.7258	0.1917	16.22	212.18	16.29	215.06	231.35	0.0678	0.9395	1.0
1.2	−22.36	0.7323	0.1614	21.23	214.50	21.32	212.54	233.86	0.0879	0.9354	1.2
1.4	−18.80	0.7381	0.1395	25.66	216.52	25.77	210.27	236.04	0.1055	0.9322	1.4
1.6	−15.62	0.7435	0.1229	29.66	218.32	29.78	208.19	237.97	0.1211	0.9295	1.6
1.8	−12.73	0.7485	0.1098	33.31	219.94	33.45	206.26	239.71	0.1352	0.9273	1.8
2.0	−10.09	0.7532	0.0993	36.69	221.43	36.84	204.46	241.30	0.1481	0.9253	2.0
2.4	−5.37	0.7618	0.0834	42.77	224.07	42.95	201.14	244.09	0.1710	0.9222	2.4
2.8	−1.23	0.7697	0.0719	48.18	226.38	48.39	198.13	246.52	0.1911	0.9197	2.8
3.2	2.48	0.7770	0.0632	53.06	228.43	53.31	195.35	248.66	0.2089	0.9177	3.2
3.6	5.84	0.7839	0.0564	57.54	230.28	57.82	192.76	250.58	0.2251	0.9160	3.6
4.0	8.93	0.7904	0.0509	61.69	231.97	62.00	190.32	252.32	0.2399	0.9145	4.0
5.0	15.74	0.8056	0.0409	70.93	235.64	71.33	184.74	256.07	0.2723	0.9117	5.0
6.0	21.58	0.8196	0.0341	78.99	238.74	79.48	179.71	259.19	0.2999	0.9097	6.0
7.0	26.72	0.8328	0.0292	86.19	241.42	86.78	175.07	261.85	0.3242	0.9080	7.0
8.0	31.33	0.8454	0.0255	92.75	243.78	93.42	170.73	264.15	0.3459	0.9066	8.0
9.0	35.53	0.8576	0.0226	98.79	245.88	99.56	166.62	266.18	0.3656	0.9054	9.0
10.0	39.39	0.8695	0.0202	104.42	247.77	105.29	162.68	267.97	0.3838	0.9043	10.0
12.0	46.32	0.8928	0.0166	114.69	251.03	115.76	155.23	270.99	0.4164	0.9023	12.0
14.0	52.43	0.9159	0.0140	123.98	253.74	125.26	148.14	273.40	0.4453	0.9003	14.0
16.0	57.92	0.9392	0.0121	132.52	256.00	134.02	141.31	275.33	0.4714	0.8982	16.0
18.0	62.91	0.9631	0.0105	140.49	257.88	142.22	134.60	276.83	0.4954	0.8959	18.0
20.0	67.49	0.9878	0.0093	148.02	259.41	149.99	127.95	277.94	0.5178	0.8934	20.0
25.0	77.59	1.0562	0.0069	165.48	261.84	168.12	111.06	279.17	0.5687	0.8854	25.0
30.0	86.22	1.1416	0.0053	181.88	262.16	185.30	92.71	278.01	0.6156	0.8735	30.0

R-134a

TABLE A-12 Properties of Superheated Refrigerant 134a Vapor

$T$ °C	$v$ m <sup>3</sup> /kg	$u$ kJ/kg	$h$ kJ/kg	$s$ kJ/kg · K	$v$ m <sup>3</sup> /kg	$u$ kJ/kg	$h$ kJ/kg	$s$ kJ/kg · K
$p = 0.6 \text{ bar} = 0.06 \text{ MPa}$ ( $T_{\text{sat}} = -37.07^\circ\text{C}$ )					$p = 1.0 \text{ bar} = 0.10 \text{ MPa}$ ( $T_{\text{sat}} = -26.43^\circ\text{C}$ )			
Sat.	0.31003	206.12	224.72	0.9520	0.19170	212.18	231.35	0.9395
-20	0.33536	217.86	237.98	1.0062	0.19770	216.77	236.54	0.9602
-10	0.34992	224.97	245.96	1.0371	0.20686	224.01	244.70	0.9918
0	0.36433	232.24	254.10	1.0675	0.21587	231.41	252.99	1.0227
10	0.37861	239.69	262.41	1.0973	0.22473	238.96	261.43	1.0531
20	0.39279	247.32	270.89	1.1267	0.23349	246.67	270.02	1.0829
30	0.40688	255.12	279.53	1.1557	0.24216	254.54	278.76	1.1122
40	0.42091	263.10	288.35	1.1844	0.25076	262.58	287.66	1.1411
50	0.43487	271.25	297.34	1.2126	0.25930	270.79	296.72	1.1696
60	0.44879	279.58	306.51	1.2405	0.26779	279.16	305.94	1.1977
70	0.46266	288.08	315.84	1.2681	0.27623	287.70	315.32	1.2254
80	0.47650	296.75	325.34	1.2954	0.28464	296.40	324.87	1.2528
90	0.49031	305.58	335.00	1.3224	0.29302	305.27	334.57	1.2799
$p = 1.4 \text{ bar} = 0.14 \text{ MPa}$ ( $T_{\text{sat}} = -18.80^\circ\text{C}$ )					$p = 1.8 \text{ bar} = 0.18 \text{ MPa}$ ( $T_{\text{sat}} = -12.73^\circ\text{C}$ )			
Sat.	0.13945	216.52	236.04	0.9322	0.10983	219.94	239.71	0.9273
-10	0.14549	223.03	243.40	0.9606	0.11135	222.02	242.06	0.9362
0	0.15219	230.55	251.86	0.9922	0.11678	229.67	250.69	0.9684
10	0.15875	238.21	260.43	1.0230	0.12207	237.44	259.41	0.9998
20	0.16520	246.01	269.13	1.0532	0.12723	245.33	268.23	1.0304
30	0.17155	253.96	277.97	1.0828	0.13230	253.36	277.17	1.0604
40	0.17783	262.06	286.96	1.1120	0.13730	261.53	286.24	1.0898
50	0.18404	270.32	296.09	1.1407	0.14222	269.85	295.45	1.1187
60	0.19020	278.74	305.37	1.1690	0.14710	278.31	304.79	1.1472
70	0.19633	287.32	314.80	1.1969	0.15193	286.93	314.28	1.1753
80	0.20241	296.06	324.39	1.2244	0.15672	295.71	323.92	1.2030
90	0.20846	304.95	334.14	1.2516	0.16148	304.63	333.70	1.2303
100	0.21449	314.01	344.04	1.2785	0.16622	313.72	343.63	1.2573
$p = 2.0 \text{ bar} = 0.20 \text{ MPa}$ ( $T_{\text{sat}} = -10.09^\circ\text{C}$ )					$p = 2.4 \text{ bar} = 0.24 \text{ MPa}$ ( $T_{\text{sat}} = -5.37^\circ\text{C}$ )			
Sat.	0.09933	221.43	241.30	0.9253	0.08343	224.07	244.09	0.9222
-10	0.09938	221.50	241.38	0.9256				
0	0.10438	229.23	250.10	0.9582	0.08574	228.31	248.89	0.9399
10	0.10922	237.05	258.89	0.9898	0.08993	236.26	257.84	0.9721
20	0.11394	244.99	267.78	1.0206	0.09399	244.30	266.85	1.0034
30	0.11856	253.06	276.77	1.0508	0.09794	252.45	275.95	1.0339
40	0.12311	261.26	285.88	1.0804	0.10181	260.72	285.16	1.0637
50	0.12758	269.61	295.12	1.1094	0.10562	269.12	294.47	1.0930
60	0.13201	278.10	304.50	1.1380	0.10937	277.67	303.91	1.1218
70	0.13639	286.74	314.02	1.1661	0.11307	286.35	313.49	1.1501
80	0.14073	295.53	323.68	1.1939	0.11674	295.18	323.19	1.1780
90	0.14504	304.47	333.48	1.2212	0.12037	304.15	333.04	1.2055
100	0.14932	313.57	343.43	1.2483	0.12398	313.27	343.03	1.2326

TABLE A-12 (Continued)

$T$ °C	$v$ m <sup>3</sup> /kg	$u$ kJ/kg	$h$ kJ/kg	$s$ kJ/kg · K	$v$ m <sup>3</sup> /kg	$u$ kJ/kg	$h$ kJ/kg	$s$ kJ/kg · K
$p = 2.8 \text{ bar} = 0.28 \text{ MPa}$ ( $T_{\text{sat}} = -1.23^\circ\text{C}$ )					$p = 3.2 \text{ bar} = 0.32 \text{ MPa}$ ( $T_{\text{sat}} = 2.48^\circ\text{C}$ )			
Sat.	0.07193	226.38	246.52	0.9197	0.06322	228.43	248.66	0.9177
0	0.07240	227.37	247.64	0.9238				
10	0.07613	235.44	256.76	0.9566	0.06576	234.61	255.65	0.9427
20	0.07972	243.59	265.91	0.9883	0.06901	242.87	264.95	0.9749
30	0.08320	251.83	275.12	1.0192	0.07214	251.19	274.28	1.0062
40	0.08660	260.17	284.42	1.0494	0.07518	259.61	283.67	1.0367
50	0.08992	268.64	293.81	1.0789	0.07815	268.14	293.15	1.0665
60	0.09319	277.23	303.32	1.1079	0.08106	276.79	302.72	1.0957
70	0.09641	285.96	312.95	1.1364	0.08392	285.56	312.41	1.1243
80	0.09960	294.82	322.71	1.1644	0.08674	294.46	322.22	1.1525
90	0.10275	303.83	332.60	1.1920	0.08953	303.50	332.15	1.1802
100	0.10587	312.98	342.62	1.2193	0.09229	312.68	342.21	1.2076
110	0.10897	322.27	352.78	1.2461	0.09503	322.00	352.40	1.2345
120	0.11205	331.71	363.08	1.2727	0.09774	331.45	362.73	1.2611
$p = 4.0 \text{ bar} = 0.40 \text{ MPa}$ ( $T_{\text{sat}} = 8.93^\circ\text{C}$ )					$p = 5.0 \text{ bar} = 0.50 \text{ MPa}$ ( $T_{\text{sat}} = 15.74^\circ\text{C}$ )			
Sat.	0.05089	231.97	252.32	0.9145	0.04086	235.64	256.07	0.9117
10	0.05119	232.87	253.35	0.9182				
20	0.05397	241.37	262.96	0.9515	0.04188	239.40	260.34	0.9264
30	0.05662	249.89	272.54	0.9837	0.04416	248.20	270.28	0.9597
40	0.05917	258.47	282.14	1.0148	0.04633	256.99	280.16	0.9918
50	0.06164	267.13	291.79	1.0452	0.04842	265.83	290.04	1.0229
60	0.06405	275.89	301.51	1.0748	0.05043	274.73	299.95	1.0531
70	0.06641	284.75	311.32	1.1038	0.05240	283.72	309.92	1.0825
80	0.06873	293.73	321.23	1.1322	0.05432	292.80	319.96	1.1114
90	0.07102	302.84	331.25	1.1602	0.05620	302.00	330.10	1.1397
100	0.07327	312.07	341.38	1.1878	0.05805	311.31	340.33	1.1675
110	0.07550	321.44	351.64	1.2149	0.05988	320.74	350.68	1.1949
120	0.07771	330.94	362.03	1.2417	0.06168	330.30	361.14	1.2218
130	0.07991	340.58	372.54	1.2681	0.06347	339.98	371.72	1.2484
140	0.08208	350.35	383.18	1.2941	0.06524	349.79	382.42	1.2746
$p = 6.0 \text{ bar} = 0.60 \text{ MPa}$ ( $T_{\text{sat}} = 21.58^\circ\text{C}$ )					$p = 7.0 \text{ bar} = 0.70 \text{ MPa}$ ( $T_{\text{sat}} = 26.72^\circ\text{C}$ )			
Sat.	0.03408	238.74	259.19	0.9097	0.02918	241.42	261.85	0.9080
30	0.03581	246.41	267.89	0.9388	0.02979	244.51	265.37	0.9197
40	0.03774	255.45	278.09	0.9719	0.03157	253.83	275.93	0.9539
50	0.03958	264.48	288.23	1.0037	0.03324	263.08	286.35	0.9867
60	0.04134	273.54	298.35	1.0346	0.03482	272.31	296.69	1.0182
70	0.04304	282.66	308.48	1.0645	0.03634	281.57	307.01	1.0487
80	0.04469	291.86	318.67	1.0938	0.03781	290.88	317.35	1.0784
90	0.04631	301.14	328.93	1.1225	0.03924	300.27	327.74	1.1074
100	0.04790	310.53	339.27	1.1505	0.04064	309.74	338.19	1.1358
110	0.04946	320.03	349.70	1.1781	0.04201	319.31	348.71	1.1637
120	0.05099	329.64	360.24	1.2053	0.04335	328.98	359.33	1.1910
130	0.05251	339.38	370.88	1.2320	0.04468	338.76	370.04	1.2179
140	0.05402	349.23	381.64	1.2584	0.04599	348.66	380.86	1.2444
150	0.05550	359.21	392.52	1.2844	0.04729	358.68	391.79	1.2706
160	0.05698	369.32	403.51	1.3100	0.04857	368.82	402.82	1.2963

TABLE A-12 (Continued)

$T$ °C	$v$ m <sup>3</sup> /kg	$u$ kJ/kg	$h$ kJ/kg	$s$ kJ/kg · K	$v$ m <sup>3</sup> /kg	$u$ kJ/kg	$h$ kJ/kg	$s$ kJ/kg · K
$p = 8.0 \text{ bar} = 0.80 \text{ MPa}$ ( $T_{\text{sat}} = 31.33^\circ\text{C}$ )					$p = 9.0 \text{ bar} = 0.90 \text{ MPa}$ ( $T_{\text{sat}} = 35.53^\circ\text{C}$ )			
Sat.	0.02547	243.78	264.15	0.9066	0.02255	245.88	266.18	0.9054
40	0.02691	252.13	273.66	0.9374	0.02325	250.32	271.25	0.9217
50	0.02846	261.62	284.39	0.9711	0.02472	260.09	282.34	0.9566
60	0.02992	271.04	294.98	1.0034	0.02609	269.72	293.21	0.9897
70	0.03131	280.45	305.50	1.0345	0.02738	279.30	303.94	1.0214
80	0.03264	289.89	316.00	1.0647	0.02861	288.87	314.62	1.0521
90	0.03393	299.37	326.52	1.0940	0.02980	298.46	325.28	1.0819
100	0.03519	308.93	337.08	1.1227	0.03095	308.11	335.96	1.1109
110	0.03642	318.57	347.71	1.1508	0.03207	317.82	346.68	1.1392
120	0.03762	328.31	358.40	1.1784	0.03316	327.62	357.47	1.1670
130	0.03881	338.14	369.19	1.2055	0.03423	337.52	368.33	1.1943
140	0.03997	348.09	380.07	1.2321	0.03529	347.51	379.27	1.2211
150	0.04113	358.15	391.05	1.2584	0.03633	357.61	390.31	1.2475
160	0.04227	368.32	402.14	1.2843	0.03736	367.82	401.44	1.2735
170	0.04340	378.61	413.33	1.3098	0.03838	378.14	412.68	1.2992
180	0.04452	389.02	424.63	1.3351	0.03939	388.57	424.02	1.3245
$p = 10.0 \text{ bar} = 1.00 \text{ MPa}$ ( $T_{\text{sat}} = 39.39^\circ\text{C}$ )					$p = 12.0 \text{ bar} = 1.20 \text{ MPa}$ ( $T_{\text{sat}} = 46.32^\circ\text{C}$ )			
Sat.	0.02020	247.77	267.97	0.9043	0.01663	251.03	270.99	0.9023
40	0.02029	248.39	268.68	0.9066				
50	0.02171	258.48	280.19	0.9428	0.01712	254.98	275.52	0.9164
60	0.02301	268.35	291.36	0.9768	0.01835	265.42	287.44	0.9527
70	0.02423	278.11	302.34	1.0093	0.01947	275.59	298.96	0.9868
80	0.02538	287.82	313.20	1.0405	0.02051	285.62	310.24	1.0192
90	0.02649	297.53	324.01	1.0707	0.02150	295.59	321.39	1.0503
100	0.02755	307.27	334.82	1.1000	0.02244	305.54	332.47	1.0804
110	0.02858	317.06	345.65	1.1286	0.02335	315.50	343.52	1.1096
120	0.02959	326.93	356.52	1.1567	0.02423	325.51	354.58	1.1381
130	0.03058	336.88	367.46	1.1841	0.02508	335.58	365.68	1.1660
140	0.03154	346.92	378.46	1.2111	0.02592	345.73	376.83	1.1933
150	0.03250	357.06	389.56	1.2376	0.02674	355.95	388.04	1.2201
160	0.03344	367.31	400.74	1.2638	0.02754	366.27	399.33	1.2465
170	0.03436	377.66	412.02	1.2895	0.02834	376.69	410.70	1.2724
180	0.03528	388.12	423.40	1.3149	0.02912	387.21	422.16	1.2980
$p = 14.0 \text{ bar} = 1.40 \text{ MPa}$ ( $T_{\text{sat}} = 52.43^\circ\text{C}$ )					$p = 16.0 \text{ bar} = 1.60 \text{ MPa}$ ( $T_{\text{sat}} = 57.92^\circ\text{C}$ )			
Sat.	0.01405	253.74	273.40	0.9003	0.01208	256.00	275.33	0.8982
60	0.01495	262.17	283.10	0.9297	0.01233	258.48	278.20	0.9069
70	0.01603	272.87	295.31	0.9658	0.01340	269.89	291.33	0.9457
80	0.01701	283.29	307.10	0.9997	0.01435	280.78	303.74	0.9813
90	0.01792	293.55	318.63	1.0319	0.01521	291.39	315.72	1.0148
100	0.01878	303.73	330.02	1.0628	0.01601	301.84	327.46	1.0467
110	0.01960	313.88	341.32	1.0927	0.01677	312.20	339.04	1.0773
120	0.02039	324.05	352.59	1.1218	0.01750	322.53	350.53	1.1069
130	0.02115	334.25	363.86	1.1501	0.01820	332.87	361.99	1.1357
140	0.02189	344.50	375.15	1.1777	0.01887	343.24	373.44	1.1638
150	0.02262	354.82	386.49	1.2048	0.01953	353.66	384.91	1.1912
160	0.02333	365.22	397.89	1.2315	0.02017	364.15	396.43	1.2181
170	0.02403	375.71	409.36	1.2576	0.02080	374.71	407.99	1.2445
180	0.02472	386.29	420.90	1.2834	0.02142	385.35	419.62	1.2704
190	0.02541	396.96	432.53	1.3088	0.02203	396.08	431.33	1.2960
200	0.02608	407.73	444.24	1.3338	0.02263	406.90	443.11	1.3212