UNIVERSITY OF JOHANNESBURG

PROGRAM	:	BACHELOR OF ENGINEERING TECHNOLOGY *CHEMICAL ENGINEERING*
SUBJECT	:	**CHEMICAL THERMODYNAMICS 2A**
CODE	:	**CTDCHA2**
DATE	:	SSA WINTER EXAMINATION 17 JULY 2019
DURATION	:	(SESSION 2) 11:30 - 14:30
WEIGHT	:	40 : 60
TOTAL MARKS	:	100

EXAMINER(S)	:	MRS N SEEDAT
MODERATOR	:	DR R HUBERTS
NUMBER OF PAGES	:	12 PAGES

REQUIREMENTS	:	Use of scientific (non-programmable) calculator is permitted (only one per candidate); graph paper

HINTS AND INSTRUCTIONS TO CANDIDATE(S):

- Purpose of assessment is to determine not only if you can write down an answer, but also to assess whether you understand the concepts, principles and expressions involved. Set out solutions in a logical and concise manner with justification for the steps followed.
- **ATTEMPT ALL QUESTIONS**. Please answer each question to the best of your ability.
- Write your details (module name and code, ID number, student number etc.) on script(s).
- Number each question clearly; questions may be answered in any order.
- Make sure that you read each question carefully before attempting to answer the question.
- Show all steps (and units) in calculations; this is a 'closed book' test.
- Ensure your responses are legible, clear and include relevant units (where appropriate).

Question One [Total: 21 Marks]

One mole of air at initial conditions of 250 K and 2 bar undergoes the following mechanically reversible changes. The air is compressed isothermally to a pressure of 3 bar, then is heated at constant volume to a pressure of 5 bar and a temperature of 350 K. The air is then returned to its initial state by an adiabatic process.

Assume air to be an ideal gas with constant heat capacities, C_V = (5/2) R and C_P = (7/2) R and R = 8.314 J/mol K.

1.1 Sketch the path of all processes on a single PV diagram. **[2]**
1.2 Calculate the work required, heat transferred, and the changes in internal energy and enthalpy of the air for each process. **[15]**
1.3 Calculate the work done, heat transferred, and the changes in internal energy and enthalpy during the entire process. **[4]**

Question Two [Total: 12 Marks]

2.1 What can be noticed about the chemical potential and fugacity of a system approaching ideality at low pressures? **[2]**
2.2 Estimate the fugacity and residual Gibbs energy (G^R) of toluene as a gas at 635.29 K (362.29°C) and 25 bar using Virial equation generalized correlations. **[10]**

All data required can be found in the appendices.

Question Three [Total: 13 Marks]

3.1 Calculate the H_{fg} and S_{fg} of steam at 155°C using the Clapeyron equation. **[10]**
3.2 Compare the answer obtained in 3.1 with tabulated values. **[3]**

Resources required can be found in the appendices.

Question Four [Total: 28 Marks]

Ethylene gas (C_2H_4) is burned with an excess of 5% air. Combustion is incomplete, with only 95% of the carbon in the fuel being converted to CO_2, the remainder appears as CO. The fuel is supplied to the burner at 25°C, while the air enters at 450 K. the final temperature of the combustion products is 1600 K. Make appropriate assumptions.

The following reactions take place:

$$C_2H_4 + 3O_2 \rightarrow 2CO_2 + 2H_2O_{(g)}$$
$$C_2H_4 + 2O_2 \rightarrow 2CO + 2H_2O_{(g)}$$

Data required can be found in the appendices.

Determine the magnitude and direction of any heat transfer in kJ/ kmol of fuel. **[28]**

Question Five **[Total: 14 Marks]**

The PVT behaviour of a certain gas is described by the equation of state provided below:

$$P(V - b) = RT$$

Where b is a constant and Cv is constant.

5.1 Show that U is a function of T only if $dU = C_v\, dT + \left[T\left(\frac{\partial P}{\partial T}\right) - P\right] dV$. **[10]**

5.2 Explain the significance of the fundamental property relations and provide the fundamental property relations for internal and Gibbs free energy. **[4]**

END **[Total: 88 Marks]**

APPENDIX A

USEFUL EQUATIONS AND FORMULAE

$PV = nRT$; $\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$; $v = \frac{V^t}{m}$; $\dot{m} = uA\rho$; $\dot{n} = \frac{uA}{vM}$;$\rho = v^{-1}$; $\dot{V} = \frac{V}{t}$

t(°C) = T(K) – 273.15; t(°F) = T(R) – 459.67; t(°F) = 1.8t(°C) + 32;

$P_g = \frac{F}{A} = \frac{mg}{A} = \frac{\rho Vg}{A} = \frac{Ah\rho g}{A}$; $P_{abs} = P_g(or\ \rho gh) + P_{atm}$

Interpolation: $M = \left(\frac{X_2 - X}{X_2 - X_1}\right)M_1 + \left(\frac{X - X_1}{X_2 - X_1}\right)M_2$ OR $M = \frac{M_1(X_2 - X) + M_2(X - X_1)}{X_2 - X_1}$

Double Interpolation:

	X_1	X	X_2
Y_1	$M_{1,1}$		$M_{1,2}$
Y		$M = ?$	
Y_2	$M_{2,1}$		$M_{2,2}$

$$M = \left[\left(\frac{X_2 - X}{X_2 - X_1}\right)M_{1,1} + \left(\frac{X - X_1}{X_2 - X_1}\right)M_{1,2}\right]\frac{Y_2 - Y}{Y_2 - Y_1} + \left[\left(\frac{X_2 - X}{X_2 - X_1}\right)M_{2,1} + \left(\frac{X - X_1}{X_2 - X_1}\right)M_{2,2}\right]\frac{Y - Y_1}{Y_2 - Y_1}$$

$\Delta E_{univ} = \Delta E_{syst} + \Delta E_{surr} = 0$; $\eta = \frac{W_{irreversible}}{W_{reversible}}$; $\frac{dm_{cv}}{dt} = \Delta m = \dot{m}_{out} - \dot{m}_{in}$

Energy balance for open systems: $\frac{d(mU)_{cv}}{dt} = -\dot{m}\Delta\left[U + \frac{1}{2}u^2 + gh\right] + \dot{Q} + \dot{W}$

Energy balance for steady-state flow processes: $\Delta\dot{m}\left(H + \frac{1}{2}u^2 + gh\right) = \dot{Q} + \dot{W}_s$

Single Phase:$\ln\frac{V_2}{V_1} = \beta(T_2 - T_1) - \kappa(P_2 - P_1)$

Mechanically reversible closed system processes:

Constant V: $Q = n\Delta U = n\int_{T_1}^{T_2} C_v dT = nC_v\Delta T$

Constant P: $Q = n\Delta H = n\int_{T_1}^{T_2} C_p dT = nC_p\Delta T$; $W = -R(T_2 - T_1)$

Constant T: $Q = -W = RT_1\ln\frac{V_2}{V_1} = -RT_1\ln\frac{P_2}{P_1} = P_1V_1\ln\frac{V_2}{V_1} = -P_1V_1\ln\frac{P_2}{P_1}$

Adiabatic: $\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{R/C_V}$; $\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{R/C_P}$; $\frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{C_P/C_V}$; $\gamma = \frac{C_P}{C_V}$;

Adiabatic: $W = \Delta U = C_V\Delta T = \frac{R\Delta T}{\gamma - 1} = \frac{R(T_2 - T_1)}{\gamma - 1} = \frac{P_2V_2 - P_1V_1}{\gamma - 1} = \frac{P_1V_1}{\gamma - 1}\left[\left(\frac{P_2}{P_1}\right)^{\gamma - 1/\gamma} - 1\right] = \frac{RT_1}{\gamma - 1}\left[\left(\frac{P_2}{P_1}\right)^{\gamma - 1/\gamma} - 1\right]$

Virial equation truncated to 2 terms: $Z = \frac{PV}{RT} = 1 + \frac{BP}{RT}$; truncated to 3 terms:$Z = 1 + \frac{B(T)}{V} + \frac{C(T)}{V^2}$;

Lee/ Kesler correlation: $Z = Z^o + \omega Z^1$;

Generalized Pitzer correlation: $Z = 1 + (B^0 + \omega B^1)\frac{P_r}{T_r}$; $B^0 = 0.083 - \frac{0.422}{T_r^{1.6}}$; $B^1 = 0.139 - \frac{0.172}{T_r^{4.2}}$

IG:$Q = n\Delta H = n\int_{T_0}^{T_1}\frac{Cp^{ig}}{R}dT \underset{\tau=\frac{T}{T_0}}{=} n\left[AT_o(\tau-1)+\frac{B}{2}T_o^2(\tau^2-1)+\frac{C}{3}T_o^3(\tau^3-1)+\frac{D}{T_o}\left(\frac{\tau-1}{\tau}\right)\right] =$
$n\frac{\langle C_P\rangle_H}{R}(T_1-T_0)$;where,

$$\langle C_P\rangle_H = R\left[A+\frac{B}{2}T_o(\tau+1)+\frac{C}{3}T_o^2(\tau^2+\tau+1)+\frac{D}{\tau T_o^2}\right]$$

Clapeyron equation: $\Delta H = T\Delta V\frac{dP^{sat}}{dT}$

Rackett equation: $V^{sat} = V_c Z_c^{(1-T_r)^{2/7}}$

General entropy change: $\Delta S = C_p \ln\frac{T_2}{T_1} - ln\frac{P_2}{P_1}$

Entropy change for IG: $\frac{\Delta S}{R} = \frac{\langle c_p^{ig}\rangle_S}{R}\ln\frac{T}{T_o} - \ln\frac{P}{P_o}$; $\frac{\langle c_p^{ig}\rangle_S}{R} = A + \left[BT_o + \left(CT_o^2 + \frac{D}{\tau^2 T_o^2}\right)\left(\frac{\tau+1}{\tau}\right)\right]\left(\frac{\tau-1}{\ln\tau}\right)$

For residual properties: $V^R = V - V^{ig}$; $H^R = H - H^{ig}$; $G^R = RT\ln\phi$

$S^R = S - (S^{ig} + \frac{R}{Mr}\ln\frac{P_2}{P_1})$; $\frac{H^R}{RT_c} = \left(\frac{H^R}{RT_c}\right)^0 + \omega\left(\frac{H^R}{RT_c}\right)^1$; $\frac{S^R}{R} = \left(\frac{S^R}{R}\right)^0 + \omega\left(\frac{S^R}{R}\right)^1$

$\frac{H^R}{RT_c} = P_r\left[\left(0.083 - \frac{1.097}{T_r^{1.6}}\right) + \omega\left(0.139 - \frac{0.894}{T_r^{4.2}}\right)\right]$; $\frac{S^R}{R} = -P_r\left[\frac{0.675}{T_r^{2.6}} + \omega\left(\frac{0.722}{T_r^{5.2}}\right)\right]$;

$$Z = 1 + \beta - q\beta\frac{(Z-\beta)}{(Z+\in\beta)(Z+\sigma\beta)}$$

Fugacity and fugacity coefficient: $\phi = \left(\phi^0\right)\left(\phi^1\right)^{\omega}; f = \phi P; \ln\phi = \sum_i X_i \ln\phi_i$; $ln\,\phi = \frac{P_r}{T_r}(B^0 + \omega B^1)$

Raoult's law: $y_i P = x_i P_i^{sat}$ where $P = \sum_i x_i P_i^{sat}$ or $P = \frac{1}{\sum_i y_i/P_i^{sat}}$

Modified Raoult's law: $y_i P = x_i\gamma_i P_i^{sat}$ where $P = \sum_i x_i\gamma_i P_i^{sat}$ or $P = \frac{1}{\sum_i y_i/\gamma_i P_i^{sat}}$

Table A.1: Conversion Factors

Quantity	Conversion
Length	$1\ m = 100\ cm$ $= 3.28084(ft) = 39.3701(in)$
Mass	$1\ kg = 10^3\ g$ $= 2.20462(lb_m)$
Force	$1\ N = 1\ kg\ m\ s^{-2}$ $= 10^5(dyne)$ $= 0.224809(lb_f)$
Pressure	$1\ bar = 10^5\ kg\ m^{-1}\ s^{-2} = 10^5\ N\ m^{-2}$ $= 10^5\ Pa = 10^2\ kPa$ $= 10^6(dyne)\ cm^{-2}$ $= 0.986923(atm)$ $= 14.5038(psia)$ $= 750.061(torr)$
Volume	$1\ m^3 = 10^6\ cm^3 = 10^3$ liters $= 35.3147(ft)^3$ $= 264.172(gal)$
Density	$1\ g\ cm^{-3} = 10^3\ kg\ m^{-3}$ $= 62.4278(lb_m)(ft)^{-3}$
Energy	$1\ J = 1\ kg\ m^2\ s^{-2} = 1\ N\ m$ $= 1\ m^3\ Pa = 10^{-5}\ m^3\ bar = 10\ cm^3\ bar$ $= 9.86923\ cm^3(atm)$ $= 10^7(dyne)\ cm = 10^7(erg)$ $= 0.239006(cal)$ $= 5.12197 \times 10^{-3}(ft)^3(psia) = 0.737562(ft)(lb_f)$ $= 9.47831 \times 10^{-4}(Btu) = 2.77778 \times 10^{-7}\ kWhr$
Power	$1\ kW = 10^3\ W = 10^3\ kg\ m^2\ s^{-3} = 10^3\ J\ s^{-1}$ $= 239.006(cal)\ s^{-1}$ $= 737.562(ft)(lb_f)\ s^{-1}$ $= 0.947831(Btu)\ s^{-1}$ $= 1.34102(hp)$

Table A.2: Values of the Universal Gas Constant

$R = 8.314\ J\ mol^{-1}\ K^{-1} = 8.314\ m^3\ Pa\ mol^{-1}\ K^{-1}$
$= 83.14\ cm^3\ bar\ mol^{-1}\ K^{-1} = 8{,}314\ cm^3\ kPa\ mol^{-1}\ K^{-1}$
$= 82.06\ cm^3(atm)\ mol^{-1}\ K^{-1} = 62{,}356\ cm^3(torr)\ mol^{-1}\ K^{-1}$
$= 1.987(cal)\ mol^{-1}\ K^{-1} = 1.986(Btu)(lb\ mole)^{-1}(R)^{-1}$
$= 0.7302(ft)^3(atm)(lb\ mol)^{-1}(R)^{-1} = 10.73(ft)^3(psia)(lb\ mol)^{-1}(R)^{-1}$
$= 1{,}545(ft)(lb_f)(lb\ mol)^{-1}(R)^{-1}$

APPENDIX B

Table C.4 Standard Enthalpies and Gibbs Energies of Formation at 298.15 K (25°C)†

Joules per mole of the substance formed

Chemical species		State (Note 2)	ΔH°_{f298} (Note 1)	ΔG°_{f298} (Note 1)
Paraffins:				
Methane	CH_4	(g)	−74 520	−50 460
Ethane	C_2H_6	(g)	−83 820	−31 855
Propane	C_3H_8	(g)	−104 680	−24 290
n-Butane	C_4H_{10}	(g)	−125 790	−16 570
n-Pentane	C_5H_{12}	(g)	−146 760	−8 650
n-Hexane	C_6H_{14}	(g)	−166 920	150
n-Heptane	C_7H_{16}	(g)	−187 780	8 260
n-Octane	C_8H_{18}	(g)	−208 750	16 260
1-Alkenes:				
Ethylene	C_2H_4	(g)	52 510	68 460
Propylene	C_3H_6	(g)	19 710	62 205
1-Butene	C_4H_8	(g)	−540	70 340
1-Pentene	C_5H_{10}	(g)	−21 280	78 410
1-Hexene	C_6H_{12}	(g)	−41 950	86 830
1-Heptene	C_7H_{14}	(g)	−62 760	
Miscellaneous organics:				
Acetaldehyde	C_2H_4O	(g)	−166 190	−128 860
Acetic acid	$C_2H_4O_2$	(l)	−484 500	−389 900
Acetylene	C_2H_2	(g)	227 480	209 970
Benzene	C_6H_6	(g)	82 930	129 665
Benzene	C_6H_6	(l)	49 080	124 520
1,3-Butadiene	C_4H_6	(g)	109 240	149 795
Cyclohexane	C_6H_{12}	(g)	−123 140	31 920
Cyclohexane	C_6H_{12}	(l)	−156 230	26 850
1,2-Ethanediol	$C_2H_6O_2$	(l)	−454 800	−323 080
Ethanol	C_2H_6O	(g)	−235 100	−168 490
Ethanol	C_2H_6O	(l)	−277 690	−174 780
Ethylbenzene	C_8H_{10}	(g)	29 920	130 890
Ethylene oxide	C_2H_4O	(g)	−52 630	−13 010
Formaldehyde	CH_2O	(g)	−108 570	−102 530
Methanol	CH_4O	(g)	−200 660	−161 960
Methanol	CH_4O	(l)	−238 660	−166 270
Methylcyclohexane	C_7H_{14}	(g)	−154 770	27 480
Methylcyclohexane	C_7H_{14}	(l)	−190 160	20 560
Styrene	C_8H_8	(g)	147 360	213 900
Toluene	C_7H_8	(g)	50 170	122 050
Toluene	C_7H_8	(l)	12 180	113 630

Table C.4 (Continued)

Chemical species		State (Note 2)	ΔH°_{f298} (Note 1)	ΔG°_{f298} (Note 1)
Miscellaneous inorganics:				
Ammonia	NH_3	(g)	−46 110	−16 450
Ammonia	NH_3	(aq)		−26 500
Calcium carbide	CaC_2	(s)	−59 800	−64 900
Calcium carbonate	$CaCO_3$	(s)	−1206 920	−1128 790
Calcium chloride	$CaCl_2$	(s)	−795 800	−748 100
Calcium chloride	$CaCl_2$	(aq)		−8101900
Calcium chloride	$CaCl_2 \cdot 6H_2O$	(s)	−2607 900	
Calcium hydroxide	$Ca(OH)_2$	(s)	−986 090	−898 490
Calcium hydroxide	$Ca(OH)_2$	(aq)		−868 070
Calcium oxide	CaO	(s)	−635 090	−604 030
Carbon dioxide	CO_2	(g)	−393 509	−394 359
Carbon monoxide	CO	(g)	−110525	−137 169
Hydrochloric acid	HCl	(g)	−92 307	−95 299
Hydrogen cyanide	HCN	(g)	135 100	124 700
Hydrogen sulfide	H_2S	(g)	−20 630	−33 560
Iron oxide	FeO	(s)	−272 000	
Iron oxide (hematite)	Fe_2O_3	(s)	−824 200	−742 200
Iron oxide (magnetite)	Fe_3O_4	(s)	−1118400	−1015 400
Iron sulfide (pyrite)	FeS_2	(s)	−178 200	−166 900
Lithium chloride	LiCl	(s)	−408 610	
Lithium chloride	$LiCl \cdot H_2O$	(s)	−712 580	
Lithium chloride	$LiCl \cdot 2H_2O$	(s)	−1012 650	
Lithium chloride	$LiCl \cdot 3H_2O$	(s)	−1311 300	
Nitric acid	HNO_3	(l)	−174 100	−80 710
Nitric acid	HNO_3	(aq)		−111 250
Nitrogen oxides	NO	(g)	90 250	86 550
	NO_2	(g)	33 180	51 310
	N_2O	(g)	82 050	104 200
	N_2O_4	(g)	9 160	97 540
Sodium carbonate	Na_2CO_3	(s)	−1130 680	−1044 440
Sodium carbonate	$Na_2CO_3 \cdot 10H_2O$	(s)	−4081 320	
Sodium chloride	NaCl	(s)	−411 153	−384 138
Sodium chloride	NaCl	(aq)		−393 133
Sodium hydroxide	NaOH	(s)	−425 609	−379 494
Sodium hydroxide	NaOH	(aq)		−419 150
Sulfur dioxide	SO_2	(g)	−296 830	−300 194
Sulfur trioxide	SO_3	(g)	−395 720	−371 060
Sulfur trioxide	SO_3	(l)	−441 040	
Sulfuric acid	H_2SO_4	(l)	−813 989	−690 003
Sulfuric acid	H_2SO_4	(aq)		−744 530
Water	H_2O	(g)	−241 818	−228 572
Water	H_2O	(l)	−285 830	−237 129

†From TRC Thermodynamic Tables—Hydrocarbons, Thermodynamics Research Center, Texas A & M Univ. System, College Station, TX; "The NBS Tables of Chemical Thermodynamic Properties," *J.* Phys. and Chem. Reference Data, vol. 11, supp. 2, 1982.

Notes

1. The standard property changes of formation ΔH°_{f298} and ΔG°_{f298} are the changes occurring when 1 mol of the listed compound is formed from its elements with each substance in its standard state at 298.15 K (25°C).
2. Standard states: ***(a)*** Gases (g): pure ideal gas at 1 bar and 298.15 K (25°C). (b) Liquids (*l*) and solids (s): pure substance at 1 bar and 298.15 K (25°C). (c) Solutes in aqueous solution (*aq*): Hypothetical ideal 1-molal solution of solute in water at 1 bar and 298.15 K (25°C).

APPENDIX C

Table C.I Heat Capacities of Gases in the Ideal-Gas State†

Constants in equation $C_P^{ig}/R = A + BT + CT^2 + DT^{-2}$ T (kelvins) from 298.15 to T_{max}

Chemical species		T_{max}	$C_{P_{max}}^{ig}/R$	A	$10^3\,B$	$10^6\,C$	$10^{-5}\,D$
Paraffins:							
Methane	CH_4	1500	4.217	1.702	9.081	−2.164	
Ethane	C_2H_6	1500	6.369	1.131	19.225	−5.561	
Propane	C_3H_8	1500	9.001	1.213	28.785	−8.824	
n-Butane	C_4H_{10}	1500	11.928	1.935	36.915	−11.402	
iso-Butane	C_4H_{10}	1500	11.901	1.677	37.853	−11.945	
n-Pentane	C_5H_{12}	1500	14.731	2.464	45.351	−14.111	
n-Hexane	C_6H_{14}	1500	17.550	3.025	53.722	−16.791	
n-Heptane	C_7H_{16}	1500	20.361	3.570	62.127	−19.486	
n-Octane	C_8H_{18}	1500	23.174	4.108	70.567	−22.208	
1-Alkenes:							
Ethylene	C_2H_4	1500	5.325	1.424	14.394	−4.392	
Propylene	C_3H_6	1500	7.792	1.637	22.706	−6.915	
1-Butene	C_4H_8	1500	10.520	1.967	31.630	−9.873	
1-Pentene	C_5H_{10}	1500	13.437	2.691	39.753	−12.447	
1-Hexene	C_6H_{12}	1500	16.240	3.220	48.189	−15.157	
1-Heptene	C_7H_{14}	1500	19.053	3.768	56.588	−17.847	
1-Octene	C_8H_{16}	1500	21.868	4.324	64.960	−20.521	
Miscellaneous organics:							
Acetaldehyde	C_2H_4O	1000	6.506	1.693	17.978	−6.158	
Acetylene	C_2H_2	1500	5.253	6.132	1.952	.....	−1.299
Benzene	C_6H_6	1500	10.259	−0.206	39.064	−13.301	
1,3-Butadiene	C_4H_6	1500	10.720	2.734	26.786	−8.882	
Cyclohexane	C_6H_{12}	1500	13.121	−3.876	63.249	−20.928	
Ethanol	C_2H_6O	1500	8.948	3.518	20.001	−6.002	
Ethylbenzene	C_8H_{10}	1500	15.993	1.124	55.380	−18.476	
Ethylene oxide	C_2H_4O	1000	5.784	−0.385	23.463	−9.296	
Formaldehyde	CH_2O	1500	4.191	2.264	7.022	−1.877	
Methanol	CH_4O	1500	5.547	2.211	12.216	−3.450	
Styrene	C_8H_8	1500	15.534	2.050	50.192	−16.662	
Toluene	C_7H_8	1500	12.922	0.290	47.052	−15.716	
Miscellaneous inorganics:							
Air		2000	3.509	3.355	0.575	.....	−0.016
Ammonia	$NH3$	1800	4.269	3.578	3.020	.....	−0.186
Bromine	Br_2	3000	4.337	4.493	0.056	.....	−0.154
Carbon monoxide	CO	2500	3.507	3.376	0.557	.....	−0.031
Carbon dioxide	CO_2	2000	4.467	5.457	1.045	.....	−1.157
Carbon disulfide	CS_2	1800	5.532	6.311	0.805	.....	−0.906
Chlorine	Cl_2	3000	4.082	4.442	0.089	.....	−0.344
Hydrogen	H_2	3000	3.468	3.249	0.422	.....	0.083
Hydrogen sulfide	H_2S	2300	4.114	3.931	1.490	.....	−0.232
Hydrogen chloride	HCl	2000	3.512	3.156	0.623	.....	0.151
Hydrogen cyanide	HCN	2500	4.326	4.736	1.359	.....	−0.725
Nitrogen	N_2	2000	3.502	3.280	0.593	.....	0.040
Nitrous oxide	N_2O	2000	4.646	5.328	1.214	.....	−0.928
Nitric oxide	NO	2000	3.590	3.387	0.629	.....	0.014
Nitrogen dioxide	$NO2$	2000	4.447	4.982	1.195	.....	−0.792
Dinitrogen tetroxide	N_2O_4	2000	9.198	11.660	2.257	.....	−2.787
Oxygen	O_2	2000	3.535	3.639	0.506	.....	−0.227
Sulfur dioxide	SO_2	2000	4.796	5.699	0.801	.....	−1.015
Sulfur trioxide	$SO3$	2000	6.094	8.060	1.056	.....	−2.028
Water	H_2O	2000	4.038	3.470	1.450	.....	0.121

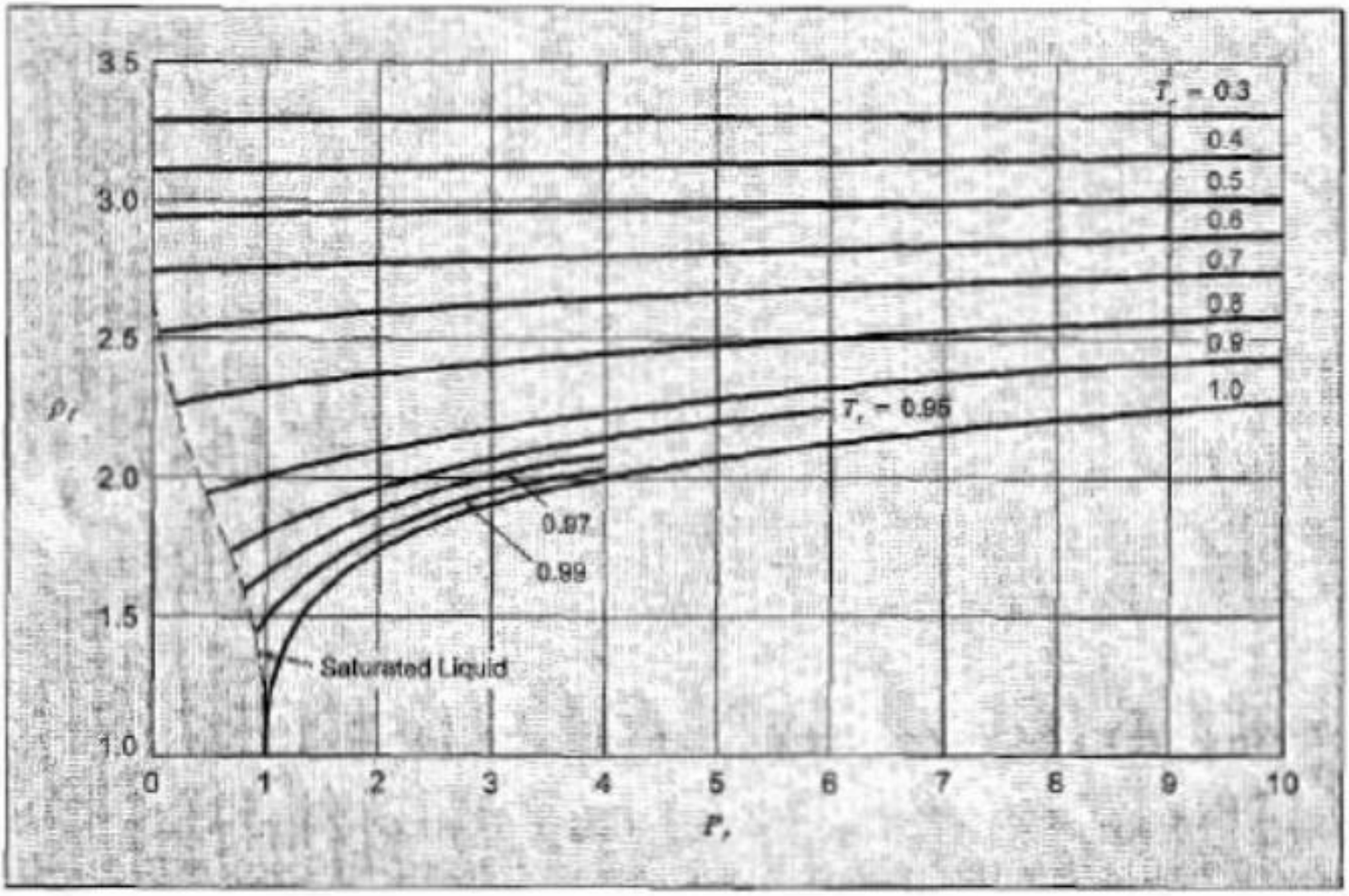
†Selected from H. M. Spencer, *Ind.* Eng. Chem., vol. 40, pp. 2152–2154, 1948; K. K. Kelley, *U.S.Bur.* Mines *Bull. 584*, 1960; *L.* B. Pankratz, U.S. *Bur.* Mines *Bull. 672*, 1982.

APPENDIX D

Table B.1 Properties of Pure Species

	Molar mass	ω	T_c/K	P_c/bar	Z_c	V_c cm^3 mol^{-1} or 10^{-3} m^3 kmol^{-1}	T_n/K
Methane	16.043	0.012	190.6	45.99	0.286	98.6	111.4
Ethane	30.070	0.100	305.3	48.72	0.279	145.5	184.6
Propane	44.097	0.152	369.8	42.48	0.276	200.0	231.1
n-Butane	58.123	0.200	425.1	37.96	0.274	255.	272.7
n-Pentane	72.150	0.252	469.7	33.70	0.270	313.	309.2
n-Hexane	86.177	0.301	507.6	30.25	0.266	371.	341.9
n-Heptane	100.204	0.350	540.2	27.40	0.261	428.	371.6
n-Octane	114.231	0.400	568.7	24.90	0.256	486.	398.8
n-Nonane	128.258	0.444	594.6	22.90	0.252	544.	424.0
n-Decane	142.285	0.492	617.7	21.10	0.247	600.	447.3
Isobutane	58.123	0.181	408.1	36.48	0.282	262.7	261.4
Isooctane	114.231	0.302	544.0	25.68	0.266	468.	372.4
Cyclopentane	70.134	0.196	511.8	45.02	0.273	258.	322.4
Cyclohexane	84.161	0.210	553.6	40.73	0.273	308.	353.9
Methylcyclopentane	84.161	0.230	532.8	37.85	0.272	319.	345.0
Methylcyclohexane	98.188	0.235	572.2	34.71	0.269	368.	374.1
Ethylene	28.054	0.087	282.3	50.40	0.281	131.	169.4
Propylene	42.081	0.140	365.6	46.65	0.289	188.4	225.5
1-Butene	56.108	0.191	420.0	40.43	0.277	239.3	266.9
cis-2-Butene	56.108	0.205	435.6	42.43	0.273	233.8	276.9
trans-2-Butene	56.108	0.218	428.6	41.00	0.275	237.7	274.0
1-Hexene	84.161	0.280	504.0	31.40	0.265	354.	336.3
Isobutylene	56.108	0.194	417.9	40.00	0.275	238.9	266.3
1,3-Butadiene	54.092	0.190	425.2	42.77	0.267	220.4	268.7
Cyclohexene	82.145	0.212	560.4	43.50	0.272	291.	356.1
Acetylene	26.038	0.187	308.3	61.39	0.271	113.	189.4
Benzene	78.114	0.210	562.2	48.98	0.271	259.	353.2
Toluene	92.141	0.262	591.8	41.06	0.264	316.	383.8
Ethylbenzene	106.167	0.303	617.2	36.06	0.263	374.	409.4
Cumene	120.194	0.326	631.1	32.09	0.261	427.	425.6
o-Xylene	106.167	0.310	630.3	37.34	0.263	369.	417.6
m-Xylene	106.167	0.326	617.1	35.36	0.259	376.	412.3
p-Xylene	106.167	0.322	616.2	35.11	0.260	379.	411.5
Styrene	104.152	0.297	636.0	38.40	0.256	352.	418.3
Naphthalene	128.174	0.302	748.4	40.51	0.269	413.	
Biphenyl	154.211	0.365	789.3	38.50	0.295	502.	528.2
Formaldehyde	30.026	0.282	408.0	65.90	0.223	115.	254.1
Acetaldehyde	44.053	0.291	466.0	55.50	0.221	154.	294.0
Methyl acetate	74.079	0.331	506.6	47.50	0.257	228.	330.1
Ethyl acetate	88.106	0.366	523.3	38.80	0.255	286.	350.2
Acetone	58.080	0.307	508.2	47.01	0.233	209.	329.4
Methyl ethyl ketone	72.107	0.323	535.5	41.50	0.249	267.	352.8
Diethyl ether	74.123	0.281	466.7	36.40	0.263	280.	307.6
Methyl t-butyl ether	88.150	0.266	497.1	34.30	0.273	329.	328.4
Methanol	32.042	0.564	512.6	80.97	0.224	118.	337.9

APPENDIX E


3.5
3.0
2.5
2.0
1.5
1.0
p_r
0
1
2
3
4
5
6
7
8
9
10
P_r
T_r = 0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
T_r = 0.95
0.97
0.99
Saturated Liquid

APPENDIX F

T C	P_{sat} kPa	v_f m3/kg	v_g m3/kg	v_{fg} m3/kg	h_f kJ/kg	h_g kJ/kg	h_{fg} kJ/kg	u_f kJ/kg	u_g kJ/kg	u_{fg} kJ/kg	s_f kJ/kg K	s_g kJ/kg K	s_{fg} kJ/kg K
112	153.173	0.001053	1.137	1.136	469.565	2694.13	2224.57	469.404	2520.03	2050.62	1.4397	7.2155	5.7758
114	163.628	0.001055	1.069	1.068	478.038	2697.10	2219.06	477.865	2522.25	2044.38	1.4616	7.1933	5.7318
116	174.662	0.001057	1.005	1.004	486.516	2700.04	2213.52	486.332	2524.46	2038.12	1.4834	7.1715	5.6880
118	186.297	0.001058	0.946389	0.945331	495.001	2702.95	2207.95	494.804	2526.64	2031.84	1.5051	7.1498	5.6447
120	198.559	0.001060	0.891572	0.890512	503.493	2705.84	2202.35	503.282	2528.81	2025.53	1.5267	7.1285	5.6017
122	211.472	0.001062	0.840500	0.839438	511.991	2708.70	2196.71	511.766	2530.96	2019.19	1.5483	7.1074	5.5591
124	225.062	0.001064	0.792881	0.791817	520.496	2711.53	2191.04	520.257	2533.09	2012.83	1.5697	7.0865	5.5168
126	239.354	0.001066	0.748448	0.747382	529.009	2714.34	2185.33	528.754	2535.19	2006.44	1.5910	7.0659	5.4749
128	254.377	0.001068	0.706958	0.705890	537.530	2717.11	2179.58	537.258	2537.28	2000.02	1.6123	7.0455	5.4332
130	270.156	0.001070	0.668188	0.667118	546.058	2719.86	2173.80	545.769	2539.34	1993.57	1.6334	7.0254	5.3919
132	286.720	0.001072	0.631933	0.630861	554.595	2722.57	2167.98	554.287	2541.38	1987.09	1.6545	7.0054	5.3510
134	304.097	0.001074	0.598007	0.596933	563.140	2725.25	2162.11	562.813	2543.40	1980.59	1.6754	6.9857	5.3103
136	322.317	0.001076	0.566238	0.565162	571.693	2727.90	2156.21	571.347	2545.39	1974.05	1.6963	6.9662	5.2699
138	341.408	0.001078	0.536469	0.535391	580.256	2730.52	2150.26	579.888	2547.36	1967.47	1.7171	6.9469	5.2298
140	361.402	0.001080	0.508556	0.507476	588.828	2733.10	2144.27	588.438	2549.31	1960.87	1.7378	6.9279	5.1900
142	382.328	0.001082	0.482365	0.481283	597.410	2735.65	2138.24	596.996	2551.23	1954.23	1.7585	6.9090	5.1505
144	404.219	0.001084	0.457774	0.456690	606.002	2738.16	2132.16	605.564	2553.12	1947.55	1.7790	6.8903	5.1113
146	427.106	0.001086	0.434672	0.433585	614.604	2740.64	2126.03	614.140	2554.98	1940.84	1.7995	6.8718	5.0723
148	451.022	0.001089	0.412954	0.411865	623.217	2743.07	2119.86	622.726	2556.82	1934.10	1.8199	6.8535	5.0336
150	476.000	0.001091	0.392524	0.391433	631.841	2745.47	2113.63	631.322	2558.63	1927.31	1.8402	6.8353	4.9952
152	502.073	0.001093	0.373295	0.372202	640.477	2747.84	2107.36	639.928	2560.41	1920.49	1.8604	6.8174	4.9570
154	529.277	0.001095	0.355186	0.354090	649.124	2750.16	2101.04	648.544	2562.17	1913.62	1.8806	6.7996	4.9190
156	557.644	0.001098	0.338120	0.337023	657.783	2752.44	2094.66	657.170	2563.89	1906.72	1.9006	6.7819	4.8813
158	587.212	0.001100	0.322029	0.320930	666.454	2754.68	2088.23	665.808	2565.58	1899.77	1.9206	6.7645	4.8438
160	618.016	0.001102	0.306849	0.305747	675.138	2756.88	2081.74	674.457	2567.24	1892.79	1.9406	6.7472	4.8066
162	650.092	0.001105	0.292519	0.291414	683.836	2759.04	2075.20	683.117	2568.87	1885.75	1.9604	6.7300	4.7696
164	683.477	0.001107	0.278985	0.277878	692.546	2761.15	2068.60	691.790	2570.47	1878.68	1.9802	6.7130	4.7328