UNIVERSITY
OF
JOHANNESBURG

PROGRAM	:	NATIONAL DIPLOMA *CHEMICAL ENGINEERING*
SUBJECT	:	**THERMODYNAMICS: CHEMICAL ENGINEERING III**
CODE	:	**CIT 3111**
DATE	:	WINTER SSA EXAMINATION 2014 15 JULY 2014
DURATION	:	(SESSION 3) 14:00 - 17:00
WEIGHT	:	40 : 60
TOTAL MARKS	:	100

EXAMINER	:	TA. MAMVURA
MODERATOR	:	DR H. RUTTO
NUMBER OF PAGES	:	3 PAGES + TABLES (4 PAGES)

INSTRUCTIONS	:	QUESTION PAPERS MUST BE HANDED IN.
REQUIREMENTS	:	CALCULATOR PERMITED
	:	ALL REQUIRED FORMULAE AND TABLES PROVIDED

INSTRUCTIONS TO CANDIDATES:
PLEASE ANSWER ALL THE QUESTIONS.

QUESTION 1

Define the following terms and give the SI units of measurement:

(a) Specific volume [4]

(b) Force [4]

(c) Pressure [4]

(d) Work [4]

(e) Heat [4]

20 MARKS

QUESTION 2

a) Calculate the standard heat of reaction of the following reaction: [10]

$$CO_{2(g)} + H_{2(g)} \rightarrow CO_{(g)} + H_2O_{(g)}$$

b) A nuclear power plant generates 750MW, the reactor temperature is 588.15K (315°C) and a river with water temperature of 293.15K (20°C) is available. What is the maximum possible thermal efficiency of the plant, and what is the minimum rate at which heat must be discarded to the river? [10]

20 MARKS

QUESTION 3

One kilomole of CO which is considered to be an ideal gas with a C_p of (7/2)R and C_v of (5/2)R at an initial state of P_1 = 2.758 MPa and T_1 = 700 K is subjected to the following processes:

(i) Isothermal expansion to P_2 = 0.552 MPa
(ii) Cooling at constant volume to T_3 = 437.5K
(iii) Cooling at constant pressure to T_4 = 350K
(iv) Adiabatic compression to P5 = 2.758 MPa
(v) Heating at constant pressure to T_6 = 700 K

Determine Q, W, ΔU and ΔH for the overall process assume reversibility

40 MARKS

QUESTION 4

Ethylene gas and steam at 593.15 K (320°C) and atmospheric pressure are fed to a reaction process as an equimolar mixture. The process produces ethanol by the reaction:

$$C_2H_{4(g)} + H_2O_{(g)} \rightarrow C_2H_5OH_{(l)}$$

The liquid ethanol exits the process at 298.15 K (25°C). What is the heat transfer associated with this overall process per mole of ethanol produced?

20 MARKS

FORMULAE

To solve these questions you may need basic equations provided:

Mechanically reversible closed processes:

1. Constant V: $Q = n\Delta U = n\int_{T_1}^{T_2} C_v dT = nC_v\Delta T$
2. Constant P: $Q = n\Delta H = n\int_{T_1}^{T_2} C_p dT = nC_p\Delta T;\ W = -R(T_2 - T_1)$
3. Constant T: $Q = -W = RT_1 \ln\frac{V_2}{V_1} = -RT_1 \ln\frac{P_2}{P_1}$
4. Adiabatic: $W = \Delta U = C_V\Delta T = \frac{RT_1}{\gamma-1}\left[\left(\frac{P_2}{P_1}\right)^{\gamma-1/\gamma} - 1\right];\qquad \gamma = \frac{C_P}{C_V}$
5. Adiabatic: $\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{R/C_V};\qquad \frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{R/C_P};\qquad \frac{P_2}{P_1} = \left(\frac{V_1}{V_2}\right)^{C_P/C_V}$
6. PVT relations: $\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$
7. Interpolation formula: $M = \left(\frac{X_2-X}{X_2-X_1}\right)M_1 + \left(\frac{X-X_1}{X_2-X_1}\right)M_2$ or $M = \frac{M_1(X_2-X)+M_2(X-X_1)}{X_2-X_1}$
8. Enthalpy of reaction: $\Delta H = R\int_{T_o}^{T}\frac{C_P}{R}dT = nR\left[\Delta A T_o(\tau-1) + \frac{\Delta B}{2}T_o^2(\tau^2-1) + \frac{\Delta C}{3}T_o^3(\tau^3-1) + \frac{\Delta D}{T_o}\left(\frac{\tau-1}{\tau}\right)\right]$
9. Enthalpy of reaction: $\Delta H = n\langle C_P\rangle_H(T - T_o)$ for $\langle C_P\rangle_H = R\left[A + \frac{B}{2}T_o(\tau+1) + \frac{C}{3}T_o^2(\tau^2+\tau+1) + \frac{D}{\tau T_o^2}\right]$
10. Entropy for an ideal gas: $\frac{\Delta S}{R} = \frac{\langle C_P^{ig}\rangle_S}{R}\ln\frac{T}{T_o} - \ln\frac{P}{P_o}$ for $\frac{\langle C_P^{ig}\rangle_S}{R} = A + \left[BT_o + \left(CT_o^2 + \frac{D}{\tau^2T_o^2}\right)\left(\frac{\tau+1}{\tau}\right)\right]\left(\frac{\tau-1}{\ln\tau}\right)$
11. For a Carnot engine: $\eta = \frac{|W_{net}|}{|Q_H|} = 1 - \frac{|Q_C|}{|Q_H|} = 1 - \frac{T_C}{T_H}$

Table A.1 Conversion Factors

Quantity	Conversion
Length	1 m = 100 cm = 3.280 84 (ft) = 39.3701 (in)
Mass	1 kg = 10^3 g = 2.204 62 (lb_m)
Force	1 N = 1 kg m s^{-2} = 10^5 (dyne) = 0.224 809 (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} = 0.986 923 atm = 14.5038 (psia) = 750.061 torr
Volume	1 m^3 = 10^6 cm^3 = 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 = 9.869 23 cm^3 atm = 10^7 dyne cm = 10^7 erg = 0.239 006 (cal) = 5.121 97 x $10^{-3}$$(ft)^3$(psia) = 0.737 562 (ft)($lb_f$) = 9.478 31 x 10^{-4} (Btu)
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} = 0.947 831 (Btu) s^{-1} = 1.341 02 (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} = 8314 cm^3 kPa mol^{-1} K^{-1}
= 82.06 cm^3 atm mol^{-1} K^{-1} = 82 363.95 cm^3 torr mol^{-1} K^{-1}= 0.082 06 m^3 atm $kmol^{-1}K^{-1}$
= 1.9872 (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)$^{-1}$
= 1545 (ft)(lb_f)(lb mol)$^{-1}$(R)$^{-1}$

Table C.1 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}	$C_{P_{mm}}^{ig}/R$	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	NH_3	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	NO_2	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	SO_3	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.

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)	$\Delta H^\circ_{f_{298}}$ (Note 1)	$\Delta G^\circ_{f_{298}}$ (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)	$\Delta H^\circ_{f_{298}}$ (Note 1)	$\Delta G^\circ_{f_{298}}$ (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 $\Delta H^\circ_{f_{298}}$ and $\Delta G^\circ_{f_{298}}$ 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).