

**Q.1 Question 1**

- (a) Derive the Maxwell relations below from the fundamental thermodynamic equations. [11 marks]

$$\begin{aligned} \left(\frac{\partial T}{\partial V}\right)_S &= -\left(\frac{\partial P}{\partial S}\right)_V; & \left(\frac{\partial T}{\partial P}\right)_S &= \left(\frac{\partial V}{\partial S}\right)_P; \\ \left(\frac{\partial P}{\partial T}\right)_V &= \left(\frac{\partial S}{\partial V}\right)_T; & \left(\frac{\partial V}{\partial T}\right)_P &= -\left(\frac{\partial S}{\partial P}\right)_T \end{aligned}$$

**Solution:**

First, let's assume a functional  $f = f(a, b)$  and rewrite it as a function of the variables  $a$  and  $b$ ,

$$df = \left(\frac{\partial f}{\partial a}\right)_b da + \left(\frac{\partial f}{\partial b}\right)_a db$$

If we define  $M = \left(\frac{\partial f}{\partial a}\right)_b$  and  $N = \left(\frac{\partial f}{\partial b}\right)_a$ , the equation above becomes

$$df = Mda + Ndb \quad (1)$$

Now, if we differentiate  $M$  and  $N$  with respect to  $b$  and  $a$ , respectively,

$$\left(\frac{\partial M}{\partial b}\right)_a = \frac{\partial^2 f}{\partial a \partial b} \quad \text{and} \quad \left(\frac{\partial N}{\partial a}\right)_b = \frac{\partial^2 f}{\partial b \partial a}$$

If the functional  $f$  is continuous and differentiable over all domain,

$$\frac{\partial^2 f}{\partial a \partial b} = \frac{\partial^2 f}{\partial b \partial a} \implies \left(\frac{\partial M}{\partial b}\right)_a = \left(\frac{\partial N}{\partial a}\right)_b \quad (2)$$

The fundamental thermodynamic relations,

$$dU = -PdV + TdS$$

$$dH = TdS + VdP$$

$$dA = -PdV - SdT$$

$$dG = -VdP - SdT$$

have similar shape as Eqn. 1, where, for example, in the first relation:

$$U = f, \quad M = -P, \quad N = T, \quad dV = da \quad \text{and} \quad dS = db.$$

Using relation 2,

$$-\left(\frac{\partial P}{\partial S}\right)_V = \left(\frac{\partial T}{\partial V}\right)_S.$$

Applying the same to the remaining relations we obtain:

$$\left(\frac{\partial T}{\partial P}\right)_S = \left(\frac{\partial V}{\partial S}\right)_P, \quad \left(\frac{\partial P}{\partial T}\right)_V = \left(\frac{\partial S}{\partial V}\right)_T, \quad \text{and} \quad \left(\frac{\partial V}{\partial T}\right)_P = -\left(\frac{\partial S}{\partial P}\right)_T$$

- (b) Using the Maxwell relations above, evaluate  $\left(\frac{\partial S}{\partial V}\right)_T$  for water vapour at 240°C and molar volume of  $0.0258 \text{ m}^3 \text{ mol}^{-1}$  through the Redlich-Kwong equation of state,

$$P = \frac{RT}{V-b} - \frac{a}{V(V+b)T^{1/2}}$$

with  $R = 8.314 \times 10^{-5} \text{ bar m}^3 (\text{mol K})^{-1}$ ,  $a = 142.59 \times 10^{-6} \text{ bar m}^6 (\text{mol K})^{-2}$  and  $b = 0.0211 \times 10^{-3} \text{ m}^3 \text{ mol}^{-1}$ . [9 marks]

**Solution:**

[2/9] *The Maxwell relation*

$$\left(\frac{\partial P}{\partial T}\right)_V = \left(\frac{\partial S}{\partial V}\right)_T$$

[4/9] *allows to determine  $\left(\frac{\partial S}{\partial V}\right)_T$  from the PVT relationship in the RK EOS. Thus,*

$$\left(\frac{\partial P}{\partial T}\right)_V = \frac{R}{V-b} + \frac{a}{2V(V+b)T^{\frac{3}{2}}}$$

[3/9] *Now substituting the variables by their values*

$$\left(\frac{\partial P}{\partial T}\right)_V = \left(\frac{\partial S}{\partial V}\right)_T = 3.2342 \times 10^{-3} \text{ bar.K}^{-1} = 3.2342 \times 10^{-1} \frac{\text{kJ}}{\text{m}^3.\text{K}}$$

**Total Question Marks:20**

**Q.2 Question 2**

- (a) A closed system with 0.09 kg of air undergoes a polytropic process from  $P_1 = 138$  kPa,  $v_1 = 0.72 \text{ m}^3 \text{ kg}^{-1}$  to a final state where  $P_2 = 552$  kPa,  $v_2 = 0.25 \text{ m}^3 \text{ kg}^{-1}$ . Determine the work (in kJ) required for this compression. [8 marks]

**Solution:**

First stage is to calculate the polytropic coefficient,

$$P_1 v_1^n = P_2 v_2^n \Rightarrow n = \frac{\ln P_2/P_1}{\ln v_1/v_2} = 1.31$$

- [4/8] Now, calculating the work with  $V_i = v_i \times m$ , thus  $V_1 = 0.0648 \text{ m}^3$  and  $V_2 = 0.0225 \text{ m}^3$ :

$$\begin{aligned} W &= - \int_{V_1}^{V_2} P dV = - \int_{V_1}^{V_2} \frac{C}{V^n} dV = - C \frac{V^{1-n}}{1-n} \Big|_{V_1}^{V_2} = - \frac{P_2 V_2^n V_2^{1-n} - P_1 V_1^n V_1^{1-n}}{1-n} = - \frac{P_2 V_2 - P_1 V_1}{1-n} \\ &= 11.214 \text{ kJ} \end{aligned}$$

- [4/8] (b) Calculate the compressibility factor ( $Z$ ) of chloroform vapour at 450 K and 20 bar (molar volume of  $1.35 \times 10^{-3} \text{ m}^3 \text{ mol}^{-1}$ ) using the Soave-Redlich-Kwong equation of state. If you are using an iterative method (i.e., hand-calculation), do use the ideal gas equation of state to estimate the initial guess,  $Z_0$ , and stop at the second iteration,  $Z_2$ . Properties of chloroform are:  $T_c = 537$  K,  $P_c = 5328.68$  kPa and  $\omega = 0.218$  (acentric factor). [12 marks]

**Solution:**

The generic form of  $Z$  is,

$$Z = 1 + \beta - q\beta \frac{Z - \beta}{(Z + \epsilon\beta)(Z + \sigma\beta)} \quad \text{with } \beta = \Omega \frac{P_r}{T_r} \quad \text{and } q = \frac{\Psi\alpha}{\Omega T_r}$$

- [2/12] For SRK with  $T_r=0.8380$ ,  $P_r=0.3754$ ,  $\beta=3.88 \times 10^{-2}$  and  $q=6.7274$ ,

$$Z = 1 + \beta - q\beta \frac{Z - \beta}{Z^2 + \beta Z}$$

- [2/12] The equation is non-linear and to find the root we can apply Newton-Raphson method

$$Z_i = Z_{i-1} - \frac{\mathcal{F}(Z_{i-1})}{d\mathcal{F}/dZ(Z_{i-1})}$$

with,

$$\begin{aligned} \mathcal{F}(Z) &= Z - \left[ 1 + \beta - q\beta \frac{Z - \beta}{Z^2 + \beta Z} \right] \\ \frac{d\mathcal{F}}{dZ}(Z) &= 1 + q\beta \frac{\beta^2 + 2\beta Z - Z^2}{(Z^2 + \beta Z)^2} \end{aligned}$$

Marks

SOLUTIONS

EX3029/2016–17

[4/12]

$$Z_1 = 0.7184$$

[4/12]

$$Z_2 = 0.7160$$

.....

[10/12]

*or (using calculator)*  $Z_{22} = 0.7088$

**Total Question Marks:20**

**Q.3 Question 3**

An ideal liquid mixture of 25 mol% n-pentane ( $nC_5$ ), 45 mol% n-hexane ( $nC_6$ ) and 30 mol% n-heptane ( $nC_7$ ), initially at 69°C and high pressure, is partially vaporised by isothermally lowering the pressure to 1.013 bar. Calculate:

- (a) Saturation pressure,  $P_i^{sat}$ , of n-pentane, n-hexane and n-heptane (in bar). [3 marks]

**Solution:**

From the Antoine equation, we can calculate the saturation pressure of the species  $P_{C_5}^{sat} = 2.721$  bar,  $P_{C_6}^{sat} = 1.024$  bar and  $P_{C_7}^{sat} = 0.389$  bar.

- (b) Vapour-liquid equilibrium constant ( $K_i = y_i \cdot x_i^{-1}$  where  $x_i$  and  $y_i$  are molar fractions of liquid and vapour phases, respectively) of all components. [6 marks]

**Solution:**

Assuming ideal solution,

$$K_i = \frac{y_i}{x_i} = \frac{P_i^{sat}}{P}$$

Thus  $K_{C_5} = 2.6861$ ,  $K_{C_6} = 1.0109$  and  $K_{C_7} = 0.3840$

- (c) Relative amounts of vapour and liquid (i.e., molar fractions of phases  $V$  and  $L$ ) in equilibrium and their compositions ( $x_i$  and  $y_i$ ). [11 marks]

**Solution:**

From  $K_i = \frac{y_i}{x_i}$ ,

$$y_{C_5} = x_{C_5} K_{C_5}, \quad y_{C_6} = x_{C_6} K_{C_6}, \quad y_{C_7} = x_{C_7} K_{C_7}$$

$$\sum_{i=1}^3 x_i = x_{C_5} + x_{C_6} + x_{C_7} = 1$$

$$\sum_{i=1}^3 y_i = y_{C_5} + y_{C_6} + y_{C_7} = 1 = K_{C_5} x_{C_5} + K_{C_6} x_{C_6} + K_{C_7} x_{C_7}$$

The mass balance is,

$$L + V = 1$$

$$x_i L + y_i V = z_i$$

with  $z_i = (0.25 \ 0.45 \ 0.30)^T$ . Rearranging this set of equations lead to a non-linear expression in  $L$ ,

$$\frac{0.25}{(1 - K_{C_5}) L + K_{C_5}} + \frac{0.45}{(1 - K_{C_6}) L + K_{C_6}} + \frac{0.30}{(1 - K_{C_7}) L + K_{C_7}} = 1$$

Solving this equation leads to  $L = 0.5748$  and  $V = 0.4252$ . Calculating the molar fractions of the species:

	n-C <sub>5</sub>	n-C <sub>6</sub>	n-C <sub>7</sub>
<b>x<sub>i</sub></b>	0.1456	0.4479	0.4065
<b>y<sub>i</sub></b>	0.3911	0.4528	0.1561

For this problem, use

$$\ln P_i^{\text{sat}} = A_i - \frac{B_i}{RT}$$

with  $[P] = \text{bar}$ ,  $[T] = \text{K}$ ,  $[B_i] = \text{J mol}^{-1}$ ,  $R [= 8.314 \text{ J (mol K)}^{-1}]$  is the molar gas constant, and

$$\begin{array}{lll} A_{nC_5} = 10.422 & A_{nC_6} = 10.456 & A_{nC_7} = 11.431 \\ B_{nC_5} = 26799 & B_{nC_6} = 29676 & B_{nC_7} = 35200 \end{array}$$

**Total Question Marks:20**

**Q.4 Question 4**

In a petrochemical plant, propane is transferred from the storage tank to a dehydrogenation reactor.

- (a) Determine the volumetric flow rate (in  $\text{m}^3\text{h}^{-1}$ ) of propane at 423 K and 71 bar using the Soave-Redlich-Kwong equation of state (SRK-EOS),

$$P = \frac{RT}{V - b} - \frac{\alpha a}{V(V + b)},$$

with

$$a = 0.42747 \frac{(RT_c)^2}{P_c}, \quad b = 0.08664 \frac{RT_c}{P_c}, \quad \alpha = \left[1 + m \left(1 - \sqrt{T_r}\right)\right]^2 \quad \text{and} \\ m = 0.48508 + 1.55171\omega - 0.1561\omega^2.$$

where  $R = 8.314 \times 10^{-5} \text{ bar m}^3 (\text{mol K})^{-1}$  is the molar gas constant and  $V$  is the molar volume. The transfer is conducted at a molar flow rate of  $10^5 \text{ mol h}^{-1}$ . Use the ideal gas law for the initial estimate of the molar volume of propane. Data for propane:  $T_c = 369.9 \text{ K}$ ,  $P_c = 42.61 \text{ bar}$  and  $\omega = 0.152$ . [13 marks]

**Solution:**

[8/13]

*The first step to solve the problem is to calculate the parameters for the SRK-EOS:*

$$a = \frac{(RT_c)^2}{P_c} = 0.42748 \frac{\left[8.314 \times 10^{-5} \frac{\text{bar.m}^3}{\text{mol.K}} \times 369.9 \text{ K}\right]^2}{42.61 \text{ bar}} = 9.4884 \times 10^{-6} \frac{\text{m}^6 \text{bar}}{\text{mol}^2} \\ b = 0.08664 \frac{RT_c}{P_c} = 6.2532 \times 10^{-5} \frac{\text{m}^3}{\text{mol}} \\ m = 0.48508 + 1.55171\omega - 0.1561\omega^2 = 0.7173 \\ \alpha = \left[1 + m \left(1 - \sqrt{T_r}\right)\right]^2 = 0.9029 \quad \text{with } T_r = \frac{T}{T_c} = 1.1436$$

*Substituting these parameters in the SRK-EOS,*

$$P = \frac{RT}{V - b} - \frac{\alpha a}{V(V + b)},$$

[2/13]

*leads to  $V = 2.8876 \times 10^{-4} \frac{\text{m}^3}{\text{mol}}$ . The volumetric flow rate is*

[3/13]

$$\dot{v} = 2.8876 \times 10^{-4} \frac{\text{m}^3}{\text{mol}} \times 10^5 \frac{\text{mol}}{\text{h}} = 28.88 \frac{\text{m}^3}{\text{h}}$$

- (b) One mole of propane gas is expanded from  $10^{-3}$  to  $4.0 \times 10^{-2} \text{ m}^3$  in a heating bath at  $100^\circ\text{C}$ . The expansion is not reversible and the heat extracted from the bath is 0.6 kJ. Determine the work for the expansion using the van der Waals equation of state (vdW-EOS),

$$P = \frac{RT}{V - b} - \frac{a}{V^2}, \quad \text{with } a = \frac{27}{64} \frac{(RT_c)^2}{P_c} \quad \text{and } b = \frac{RT_c}{8P_c}.$$

For your calculation, consider  $a = 9.126 \times 10^{-3} \text{ m}^3 \text{ bar mol}^{-1}$  and the molar internal energy [7 marks]

$$dU = \left[ T \left( \frac{\partial P}{\partial T} \right)_V - P \right] dV$$

**Solution:**

From the First law –  $\Delta U = Q + W$ , with the amount of heat transferred given as 600 J/mol. Therefore, we need to evaluate  $\Delta U$  to calculate the work. The variation of molar internal energy,

$$dU = \left[ T \left( \frac{\partial P}{\partial T} \right)_V - P \right] dV$$

[2/7]

In order to obtain  $\left( \frac{\partial P}{\partial T} \right)_V$ , we can differentiate the vdW-EOS with respect to the temperature,

$$\left( \frac{\partial P}{\partial T} \right)_V = \frac{R}{V - b}$$

[1/7]

and the term in the brackets is,

$$T \left( \frac{\partial P}{\partial T} \right)_V - P = \frac{a}{V^2}$$

[2/7]

Therefore, the variation of molar internal energy is

$$\begin{aligned} \Delta U &= \int_{0.001 \text{ m}^3}^{0.04 \text{ m}^3} \left[ T \left( \frac{\partial P}{\partial T} \right)_V - P \right] dV = \int_{0.001 \text{ m}^3}^{0.04 \text{ m}^3} \frac{a}{V^2} dV = - \frac{a}{V} \Big|_{0.001 \text{ m}^3}^{0.04 \text{ m}^3} \\ &= 8.8979 \frac{\text{m}^3 \cdot \text{bar}}{\text{mol}} = 889790 \text{ J} \cdot \text{mol}^{-1}, \end{aligned}$$

[2/7]

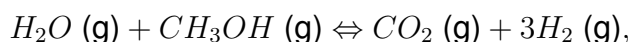
And the work is  $W = \Delta U - Q = 889.19 \text{ kJ} \cdot \text{mol}^{-1}$

**Total Question Marks:20**



**Q.5 Question 5**

The methanol steam reforming reaction for hydrogen generation is given by the following chemical reaction,



with the thermodynamic data at 25°C,

	$H_2O (g)$	$CH_3OH (g)$	$CO_2 (g)$	$H_2 (g)$
$\Delta G_{f,298}^\circ$ (kJ mol <sup>-1</sup> )	-228.57	-161.96	-394.36	0.0
$\Delta H_{f,298}^\circ$ (kJ mol <sup>-1</sup> )	-241.82	-200.66	-393.51	0.0

where  $G_{f,298}^\circ$  and  $H_{f,298}^\circ$  are the standard molar free Gibbs energy and enthalpy of formation, respectively. Determine:

- (a) The equilibrium constant,  $K_{eq}$ , at 25°C.

[7 marks]

**Solution:**

The equilibrium constant at 25°C is given by

$$K_{eq,298} = \exp \left[ -\frac{\Delta G_{mix,298}^\circ}{RT} \right].$$

The first step is to calculate the standard free Gibbs energy change of the mixture,  $\Delta G_{mix,298}^\circ$ ,

$$\begin{aligned} \Delta G_{mix,298}^\circ &= (\Delta G_{f,298}^\circ)_{CO_2} + 3 (\Delta G_{f,298}^\circ)_{H_2} - (\Delta G_{f,298}^\circ)_{H_2O} - (\Delta G_{f,298}^\circ)_{CH_3OH} \\ &= -3.83 \text{ kJ.mol}^{-1} \end{aligned}$$

The equilibrium constant can then be calculated,

$$K_{eq,298} = \exp \left[ -\frac{\Delta G_{mix,298}^\circ}{RT} \right] = \exp \left[ -\frac{3830}{8.314 \times 298.15} \right] = 4.6884$$

- (b) The equilibrium constant,  $K_{eq}$ , at 60°C.

[13 marks]

**Solution:**

The equilibrium constant of the chemical reaction can be expressed as a function of the temperature through the Van't Hoff relation:

$$\frac{d}{dT} \ln K_{eq} = \frac{\Delta H_{mix,298}^\circ}{RT^2},$$

As data is available at 25°C (= 298.15 K) and we need it at 60°C, we can integrate the Van't Hoff equation assuming constant  $\Delta H_{298}^\circ$ ,

$$\begin{aligned} \Delta H_{mix,298}^\circ &= \Delta H_{f,298}^\circ = \sum \nu_i (\Delta H_{f,298}^\circ)_i \\ &= (\Delta H_{f,298}^\circ)_{CO_2} + 3 (\Delta H_{f,298}^\circ)_{H_2} - (\Delta H_{f,298}^\circ)_{H_2O} - (\Delta H_{f,298}^\circ)_{CH_3OH} \\ &= 48.97 \text{ kJ.mol}^{-1} \end{aligned}$$

The equilibrium constant at 25°C is given by

$$K_{eq,298} = \exp \left[ -\frac{\Delta G_{mix,298}^{\circ}}{RT} \right],$$

therefore, we first need to obtain  $\Delta G_{mix,298}^{\circ}$ ,

$$\begin{aligned}\Delta G_{mix,298}^{\circ} &= (\Delta G_{f,298}^{\circ})_{CO_2} + 3 (\Delta G_{f,298}^{\circ})_{H_2} - (\Delta G_{f,298}^{\circ})_{H_2O} - (\Delta G_{f,298}^{\circ})_{CH_3OH} \\ &= -3.83 \text{ kJ.mol}^{-1}\end{aligned}$$

Thus,

$$K_{eq,298} = \exp \left[ -\frac{\Delta G_{mix,298}^{\circ}}{RT} \right] = \exp \left[ -\frac{3830}{8.314 \times 298.15} \right] = 4.6884$$

[8/13]

Now, we can proceed with the integration of the Van't Hoff equation,

$$\frac{d}{dT} (\ln K_{eq}) = \frac{\Delta H_{mix,298}^{\circ}}{RT^2} \Rightarrow \int_{K_{eq}^{298.15K}}^{K_{eq}^{333.15K}} d(\ln K_{eq}) = \frac{\Delta H_{mix,298}^{\circ}}{R} \int_{298.15K}^{333.15K} \frac{1}{T^2} dT$$

$$\begin{aligned}\ln \frac{K_{eq}^{333.15K}}{K_{eq}^{298.15K}} &= -\frac{\Delta H_{mix,298}^{\circ}}{R} \frac{1}{T} \Big|_{298.15K}^{333.15K} \\ K_{eq}^{333.15K} &= 4.6884 \exp \left[ -\frac{48970}{8.314} \left( \frac{1}{333.15} - \frac{1}{298.15} \right) \right] = 37.3580\end{aligned}$$

For this problem the equilibrium constant at 25°C is given by

$$K_{eq,298} = \exp \left[ -\frac{\Delta G_{mix,298}^{\circ}}{RT} \right]$$

where  $\Delta G_{mix,298}^{\circ}$  is the standard free Gibbs energy change of the mixture. Also the Van't Hoff equation is

$$\frac{d}{dT} \ln K_{eq} = \frac{\Delta H_{mix,298}^{\circ}}{RT^2},$$

where  $\Delta H_{mix,298}^{\circ}$  is the standard enthalpy change of the mixture and  $R [= 8.314 \text{ J (mol K)}^{-1}]$  is the molar gas constant.

**Total Question Marks:20**

**END OF PAPER**

**Total Paper Marks:100**

## 1. Fundamentals of Thermodynamics:

$$dU = dQ + dW; \quad dW = -PdV; \quad C_v = \left( \frac{\partial U}{\partial T} \right)_V; \quad C_p = \left( \frac{\partial H}{\partial T} \right)_P;$$

$$C_p - C_v = R; \quad TV^{\gamma-1} = \text{const}; \quad TP^{\frac{1-\gamma}{\gamma}} = \text{const}; \quad PV^\gamma = \text{const}$$

$$dH = dU + d(PV); \quad dS = \frac{dQ}{T}; \quad PV = nRT$$

## 2. Volumetric Properties of Pure Fluids:

$$\Psi = 2 + \mathcal{C} - \mathcal{P} - \mathcal{R}; \quad \beta = \frac{1}{V} \left( \frac{\partial V}{\partial T} \right)_P; \quad \kappa = -\frac{1}{V} \left( \frac{\partial V}{\partial P} \right)_T; \quad T_r = \frac{T}{T_c}; \quad P_r = \frac{P}{P_c}; \quad PV = ZRT$$

$$Z = 1 + \frac{BP}{RT} = 1 + \frac{BP_c}{RT_c} \frac{P_r}{T_r}; \quad \frac{BP_c}{RT_c} = B^0 + \omega B^1; \quad B^0 = 0.083 - \frac{0.422}{T_r^{1.6}}; \quad B^1 = 0.139 - \frac{0.172}{T_r^{4.2}}$$

$$P = \frac{RT}{V-b} - \frac{a}{V^2}; \quad a = \frac{27}{64} \frac{R^2 T_c^2}{P_c}; \quad b = \frac{1}{8} \frac{RT_c}{P_c}; \quad [\text{van der Waals (vdW) EOS}]$$

$$P = \frac{RT}{V-b} - \frac{a}{V\sqrt{T}(V+b)}; \quad a = \frac{0.42748R^2 T_c^{2.5}}{P_c}; \quad b = \frac{0.08664RT_c}{P_c}; \quad [\text{Redlich-Kwong (RK) EOS}]$$

$$P = \frac{RT}{V-b} - \frac{a\alpha}{V(V+b)}; \quad a = \frac{0.42748R^2 T_c^2}{P_c}; \quad b = \frac{0.08664RT_c}{P_c} \quad \text{and}$$

$$\alpha = \left[ 1 + (0.480 + 1.574\omega - 0.176\omega^2) (1 - \sqrt{T_r}) \right]^2; \quad [\text{Soave-Redlich-Kwong (SRK) EOS}]$$

$$P = \frac{RT}{V-b} - \frac{a\alpha}{V(V+b) + b(V-b)}; \quad a = \frac{0.45274R^2 T_c^2}{P_c}; \quad b = \frac{0.07780RT_c}{P_c}; \quad \text{and}$$

$$\alpha = \left[ 1 + \kappa (1 - \sqrt{T_r}) \right]^2; \quad \kappa = 0.37464 + 1.54226\omega - 0.26992\omega^2; \quad [\text{Peng-Robinson (PR) EOS}]$$

$$Z_{\text{vap}} = 1 + \beta - q\beta \frac{Z_{\text{vap}} - \beta}{(Z_{\text{vap}} + \varepsilon\beta)(Z_{\text{vap}} + \sigma\beta)}; \quad [\text{Vapour \& Vapour-like Roots}]$$

$$Z_{\text{liq}} = 1 + \beta + (Z_{\text{liq}} + \varepsilon\beta)(Z_{\text{liq}} + \sigma\beta) \left( \frac{1 + \beta - Z_{\text{liq}}}{q\beta} \right); \quad [\text{Liquid \& Liquid-like Roots}]$$

$$\beta = \Omega \frac{P_r}{T_r}; \quad q = \frac{\Psi\alpha}{\Omega T_r}; \quad \alpha_{\text{SRK}} = \left[ 1 + (0.480 + 1.574\omega - 0.176\omega^2) (1 - \sqrt{T_r}) \right]^2; \quad \text{and}$$

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

EOS	$\alpha$	$\sigma$	$\varepsilon$	$\Omega$	$\Psi$
vdW	1	0	0	1/8	27/64
RK	$T_r^{-1/2}$	1	0	0.08664	0.42748
SRK	$\alpha_{\text{SRK}}$	1	0	0.08664	0.42748
PR	$\alpha_{\text{PR}}$	$1+\sqrt{2}$	$1-\sqrt{2}$	0.07780	0.45724

Table 1: Parameters for the generic form of cubic equations of state.

$$Z_{\text{vap}}^{(i+1)} = Z_{\text{vap}}^{(i)} - \frac{F(Z_{\text{vap}}^{(i)})}{F'(Z_{\text{vap}}^{(i)})}; \quad (\text{Root-finder expression for the Newton-Raphson method})$$

## 3. Thermodynamic Properties of Pure Fluids:

$$H = U + PV; \quad G = H - TS; \quad A = U - TS;$$

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

$$\left(\frac{\partial T}{\partial V}\right)_S = -\left(\frac{\partial P}{\partial S}\right)_V; \quad \left(\frac{\partial T}{\partial P}\right)_S = \left(\frac{\partial V}{\partial S}\right)_P; \quad \left(\frac{\partial S}{\partial V}\right)_T = \left(\frac{\partial P}{\partial T}\right)_V; \quad \text{and}$$

$$-\left(\frac{\partial S}{\partial P}\right)_T = \left(\frac{\partial V}{\partial T}\right)_P; \quad (\text{Maxwell relations})$$

$$\left(\frac{\partial U}{\partial S}\right)_V = T = \left(\frac{\partial H}{\partial S}\right)_P; \quad \left(\frac{\partial U}{\partial V}\right)_S = -P = \left(\frac{\partial A}{\partial V}\right)_T; \quad \left(\frac{\partial H}{\partial P}\right)_S = V = \left(\frac{\partial G}{\partial P}\right)_T; \quad \text{and}$$

$$\left(\frac{\partial A}{\partial T}\right)_V = -S = \left(\frac{\partial G}{\partial T}\right)_P$$

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

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

$$d\left(\frac{G}{RT}\right) = \frac{V}{RT} dP - \frac{H}{RT^2} dT \quad (\text{Generating function});$$

$$M^R = M - M^{\text{ig}}; \quad \frac{H^R}{RT} = -T \int_0^P \left(\frac{\partial Z}{\partial T}\right)_P \frac{dP}{P}; \quad \frac{S^R}{R} = -T \int_0^P \left(\frac{\partial Z}{\partial T}\right)_P \frac{dP}{P} - \int_0^P (Z-1) \frac{dP}{P}; \quad \text{and}$$

$$\frac{G^R}{RT} = \int_0^P (Z-1) \frac{dP}{P} \quad (\text{Residual properties});$$

$$\frac{dP^{\text{sat}}}{dT} = \frac{\Delta H^{\alpha\beta}}{T\Delta V^{\alpha\beta}}; \quad \frac{d(\ln P^{\text{sat}})}{dT} = \frac{\Delta H^{\text{fg}}}{RT^2}; \quad (\text{Clapeyron relations})$$

$$x^{(V)} = \frac{M - M^{(L)}}{M^{(V)} - M^{(L)}} \quad (\text{Quality of vapour});$$

## 4. Vapour-Liquid Equilibrium of Mixtures:

$$x_i = \frac{n_i^{(L)}}{n}; \quad y_i = \frac{n_i^{(V)}}{n}; \quad \sum_{i=1}^c x_i = 1; \quad \sum_{i=1}^c y_i = 1 \quad (\text{Molar fraction of liquid and vapour phases});$$

$$\bar{M}_i = \left(\frac{\partial(nM)}{\partial n_i}\right)_{T,P,n_{j \neq i}} \quad (\text{Partial molar property}); \quad M^E = M - M^{\text{id}} \quad (\text{Excess properties})$$

$$\mu_i = \left(\frac{\partial(nG)}{\partial n_i}\right)_{T,P,n_{j \neq i}} = \bar{G}_i; \quad dG = VdP - SdT + \sum_i \mu_i dx_i;$$

$$P_i = y_i P = x_i \gamma_i P_i^{\text{sat}} \quad (\text{Raoult's law}); \quad P = \sum_{i=1}^c P_i = \sum_{i=1}^c y_i P; \quad T_c^t = \sum_{i=1}^c y_i T_{c,i}; \quad P_c^t = \sum_{i=1}^c y_i P_{c,i};$$

$$P_i = y_i P = x_i \mathcal{H}_i \quad (\text{Henry's law});$$

$$K_i = \frac{P_i^{\text{sat}}}{P} = \frac{y_i}{x_i}; \quad F = V + L; \quad Fz_i = x_i L + y_i V; \quad \sum_{i=1}^c \frac{z_i K_i}{1 + V(K_i - 1)} = 1;$$

## 5. Solution Thermodynamics:

$$RT \left( \frac{\partial \ln f}{\partial P} \right)_T = v; \quad \lim_{P \rightarrow 0} \frac{f}{P} = 1; \quad RT \ln \left( \frac{\bar{f}_i}{y_i f_i} \right) = \int_0^P (\bar{V}_i - \bar{v}_i) dP$$

$$\bar{f}_i^V = y_i P' \quad \text{and} \quad \bar{f}_i^L = x_i f_i^L \quad (\text{Lewis-Randall relation});$$

$$\mu_i - \mu_i^0 = RT \ln \left( \frac{\bar{f}_i}{f_i^0} \right); \quad a_i = \frac{\bar{f}_i}{f_i^0}; \quad \gamma_i = \frac{a_i}{y_i} = \frac{\bar{f}_i}{x_i f_i};$$

$$\phi_i = \frac{f_i}{P}; \quad G_i^R = G_i - G_i^{\text{ig}} = RT \ln \left( \frac{f_i}{P} \right) = RT \ln \phi_i;$$

$$f_i^L(P) = \phi_i^{\text{sat}} P_i^{\text{sat}} \exp \left[ \frac{V_i^L (P - P_i^{\text{sat}})}{RT} \right]$$

$$\left( \frac{\partial M}{\partial T} \right)_{P,x} dT + \left( \frac{\partial M}{\partial P} \right)_{T,x} dP - \sum_{i=1}^c x_i d\bar{M}_i = 0 \quad (\text{Gibbs-Duhem equation})$$

$$\sum_i x_i d\bar{M}_i = 0; \quad \sum_i x_i \frac{d\bar{M}_i}{dx_j} = 0;$$

$$M^E = M - \sum_i x_i M_i; \quad \bar{M}_1 = M + x_2 \frac{dM}{dx_1}; \quad \bar{M}_2 = M - x_1 \frac{dM}{dx_1}$$

$$x_1 \frac{d\bar{M}_1}{dx_1} + x_2 \frac{d\bar{M}_2}{dx_1} = 0; \quad \frac{d\bar{M}_1}{dx_1} = -\frac{x_2}{x_1} \frac{d\bar{M}_2}{dx_1}$$

$$PV^{\text{igm}} = \left( \sum_{i=1}^c n_i \right) RT; \quad \bar{V}_i^{\text{igm}}(T, P, y) = \frac{RT}{P} = \bar{V}_i^{\text{ig}}(T, P); \quad P_i^{\text{igm}} \left( \sum_{i=1}^c n_i, V, T, y \right) = \frac{n_i RT}{V} = P_i^{\text{ig}}(n_i, V, T);$$

$$\bar{U}^{\text{igm}}(T, y) = \sum_{i=1}^c y_i \bar{U}_i^{\text{ig}}(T); \quad \bar{H}^{\text{igm}}(T, P, y) = \sum_{i=1}^c y_i \bar{H}_i^{\text{ig}}(T, P); \quad \bar{V}^{\text{igm}}(T, P, y) = \sum_{i=1}^c y_i \bar{V}_i^{\text{ig}}(T, P)$$

$$\bar{S}^{\text{igm}}(T, P, y) = \sum_{i=1}^c y_i \bar{S}_i^{\text{ig}}(T, P) - R \sum_{i=1}^c y_i \ln y_i; \quad \bar{G}^{\text{igm}}(T, P, y) = \sum_{i=1}^c y_i \bar{G}_i^{\text{ig}}(T, P) + RT \sum_{i=1}^c y_i \ln y_i; \quad \text{and}$$

$$\bar{A}^{\text{igm}}(T, P, y) = \sum_{i=1}^c y_i \bar{A}_i^{\text{ig}}(T, P) + RT \sum_{i=1}^c y_i \ln y_i$$

$$M^{\text{id}} = \sum_i x_i \bar{M}_i^{\text{id}}; \quad V^{\text{id}} = \sum_i x_i V_i; \quad H^{\text{id}} = \sum_i x_i H_i; \quad S^{\text{id}} = \sum_i x_i S_i - R \sum_i x_i \ln x_i \quad \text{and}$$

$$G^{\text{id}} = \sum_i x_i G_i - RT \sum_i x_i \ln x_i;$$

$$d \left( \frac{nG^E}{RT} \right) = \frac{nV^E}{RT} dP - \frac{nH^E}{RT^2} dT + \sum_i \ln \gamma_i dn_i; \quad \frac{V^E}{RT} = \left( \frac{\partial \left( \frac{G^E}{RT} \right)}{\partial P} \right)_{T,x}; \quad \frac{H^E}{RT} = -T \left( \frac{\partial \left( \frac{G^E}{RT} \right)}{\partial T} \right)_{P,x};$$

$$\ln \gamma_i = \left( \frac{\partial \left( \frac{G^E}{RT} \right)}{\partial n_i} \right)_{T,P,n_j (n_j \neq n_i)}; \quad \bar{G}_i^E = RT \ln \gamma_i;$$

$$\ln \gamma_1 = x_2^2 [A_{12} + 2(A_{21} - A_{12})x_1]; \quad \ln \gamma_2 = x_1^2 [A_{21} + 2(A_{12} - A_{21})x_2]; \quad (\text{Margules activity model});$$

$$\ln \gamma_1 = B_{12} \left(1 + \frac{B_{12}x_1}{A_{21}x_2}\right)^{-2}; \quad \ln \gamma_2 = B_{21} \left(1 + \frac{B_{21}x_1}{A_{12}x_2}\right)^{-2}; \quad (\text{Van Laar activity model});$$

$$\frac{G^E}{RT} = x_1 \ln(x_1 + x_2 C_{12}) - x_2 \ln(x_2 + x_1 C_{21}) \quad \text{with}$$

$$\ln \gamma_1 = -\ln(x_1 + x_2 C_{12}) + x_2 \left( \frac{C_{12}}{x_1 + x_2 C_{12}} - \frac{C_{21}}{x_2 + x_1 C_{21}} \right) \quad \text{and}$$

$$\ln \gamma_2 = -\ln(x_2 + x_1 C_{21}) + x_1 \left( \frac{C_{12}}{x_1 + x_2 C_{12}} - \frac{C_{21}}{x_2 + x_1 C_{21}} \right);$$

## 6. Chemical Reaction Equilibrium:

$$\sum_{i=1}^C \nu_i A_i = 0; \quad d\epsilon = \frac{dn_i}{\nu_i}; \quad \sum_i n_i = \sum_i n_{i0} + \epsilon \sum_i \nu_i; \quad n = n_0 + \nu \epsilon$$

$$y_i = \frac{n_i}{n} = \frac{n_{i0} + \nu_i \epsilon}{n_0 + \nu \epsilon}$$

$$\sum_i \nu_i G_i = \sum_i \nu_i \mu_i = 0; \quad \prod_i \left( \frac{\bar{f}_i}{f_i^0} \right)^{\nu_i} = \prod_i a_i^{\nu_i} = K = \exp \left( \frac{-\Delta G^0}{RT} \right);$$

$$\Delta H^0 = -RT^2 \frac{d}{dT} (\Delta G^0 / RT) \quad (\text{Standard heat of reaction});$$

$$\frac{d(\ln K)}{dT} = \frac{\Delta H^0}{RT^2} \quad (\text{Van't Hoff equation});$$

$$\prod_i (y_i \phi_i)^{\nu_i} = K \left( \frac{P}{P^0} \right)^{-\nu}, \quad \text{where } \nu = \sum_i \nu_i \quad (\text{gas-phase});$$

$$\prod_i (y_i \gamma_i)^{\nu_i} = K \exp \left[ \frac{P^0 - P}{RT} \sum_i (\nu_i V_i) \right]^{-\nu} \quad (\text{liquid-phase});$$

$$\prod_i (y_i)^{\nu_{i,j}} = \left( \frac{P}{P^0} \right)^{-\nu_{i,j}} K_j; \quad (\text{ideal gas multi-reaction})$$

# 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<sup>2</sup> = 9.807 m/s<sup>2</sup>  
 Gravitational constant,  $k_G = 6.67 \times 10^{-11}$  m<sup>3</sup>/(kg·s<sup>2</sup>)  
 Newton's second law constant,  $g_c = 32.174$  lbm·ft/(lbf·s<sup>2</sup>) = 1.0 kg·m/(N·s<sup>2</sup>)  
 Planck's constant,  $h = 6.626 \times 10^{-34}$  J·s/molecule  
 Stefan-Boltzmann constant,  $\sigma = 0.1714 \times 10^{-8}$  Btu/(h·ft<sup>2</sup>·R<sup>4</sup>) =  $5.670 \times 10^{-8}$  W/(m<sup>2</sup>·K<sup>4</sup>)  
 Universal gas constant  $\mathfrak{R} = 1545.35$  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<sup>3</sup>/(kgmole·K) = 82.05 L·atm/(kgmole·K)  
 Velocity of light in a vacuum,  $c = 9.836 \times 10^8$  ft/s =  $2.998 \times 10^8$  m/s

## UNIT DEFINITIONS

1 coulomb (C) = 1 A·s	1 ohm ( $\Omega$ ) = 1 V/A
1 dyne = 1 g·cm/s <sup>2</sup>	1 pascal (Pa) = 1 N/m <sup>2</sup>
1 erg = 1 dyne·cm	1 poundal = 1 lbm·ft/s <sup>2</sup>
1 farad (F) = 1 C/V	1 siemens (S) = 1 A/V
1 henry (H) = 1 Wb/A	1 slug = 1 lbf·s <sup>2</sup> /ft
1 hertz (Hz) = 1 cycle/s	1 tesla (T) = 1 Wb/m <sup>2</sup>
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 <sup>2</sup>	1 weber (Wb) = 1 V·s
1 newton (N) = 1 kg·m/s <sup>2</sup>	

## CONVERSION FACTORS

Length	Energy
1 m = 3.2808 ft = 39.37 in = 10 <sup>2</sup> cm = 10 <sup>10</sup> Å	1 J = 1 N·m = 1 kg·m <sup>2</sup> /s <sup>2</sup> = 9.479 × 10 <sup>-4</sup> Btu
1 cm = 0.0328 ft = 0.394 in = 10 <sup>-2</sup> m = 10 <sup>8</sup> Å	1 kJ = 1000 J = 0.9479 Btu = 238.9 cal
1 mm = 10 <sup>-3</sup> m = 10 <sup>-1</sup> 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 <sup>-3</sup> 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 <sup>2</sup> /s <sup>2</sup> = 10 <sup>-7</sup> J
1 mile = 5280 ft = 1609.36 m = 1.609 km	1 eV = 1.602 × 10 <sup>-19</sup> J

(Continued)

**CONVERSION FACTORS** (Continued)**Area**

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

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

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

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

**Volume**

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

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

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

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

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

**Mass**

$$1 \text{ kg} = 1000 \text{ g} = 2.2046 \text{ lbm} = 0.0685 \text{ slug}$$

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

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

**Force**

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

$$1 \text{ lbf} = 4.448 \text{ N} = 32.174 \text{ poundals}$$

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

**Power**

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

$$1 \text{ kW} = 1000 \text{ W} = 3412 \text{ Btu/h} = 737.3 \text{ ft} \cdot \text{lbf/s} = 1.3405 \text{ hp}$$

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

$$1 \text{ hp} = 550 \text{ ft} \cdot \text{lbf/s} = 33000 \text{ ft} \cdot \text{lbf/min} = 2545 \text{ Btu/h} = 746 \text{ W}$$

**Pressure**

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

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

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

$$= 101.325 \text{ kPa} = 760 \text{ mm Hg}$$

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

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

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

$$1 \text{ in H}_2\text{O} = 248.8 \text{ Pa} = 0.0361 \text{ lbf/in}^2$$

**MISCELLANEOUS UNIT CONVERSIONS****Specific Heat Units**

$$1 \text{ Btu}/(\text{lbm} \cdot ^\circ\text{F}) = 1 \text{ Btu}/(\text{lbm} \cdot \text{R})$$

$$1 \text{ kJ}/(\text{kg} \cdot \text{K}) = 0.23884 \text{ Btu}/(\text{lbm} \cdot \text{R}) = 185.8 \text{ ft} \cdot \text{lbf}/(\text{lbm} \cdot \text{R})$$

$$1 \text{ Btu}/(\text{lbm} \cdot \text{R}) = 778.16 \text{ ft} \cdot \text{lbf}/(\text{lbm} \cdot \text{R}) = 4.186 \text{ kJ}/(\text{kg} \cdot \text{K})$$

**Energy Density Units**

$$1 \text{ kJ/kg} = 1000 \text{ m}^2/\text{s}^2 = 0.4299 \text{ Btu/lbm}$$

$$1 \text{ Btu/lbm} = 2.326 \text{ kJ/kg} = 2326 \text{ m}^2/\text{s}^2$$

**Energy Flux**

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

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

**Heat Transfer Coefficient**

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

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

**Thermal Conductivity**

$$1 \text{ W}/(\text{m} \cdot \text{K}) = 0.5778 \text{ Btu}/(\text{h} \cdot \text{ft} \cdot \text{R})$$

$$1 \text{ Btu}/(\text{h} \cdot \text{ft} \cdot \text{R}) = 1.731 \text{ W}/(\text{m} \cdot \text{K})$$

**Temperature**

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

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

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

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

**Density**

$$1 \text{ lbm/ft}^3 = 16.0187 \text{ kg/m}^3$$

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

$$1 \text{ g/cm}^3 = 1 \text{ kg/L} = 62.4 \text{ lbm/ft}^3 = 10^3 \text{ kg/m}^3$$

**Viscosity**

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

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

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

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

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

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

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

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