**Q.1** | **Question 1**

(a) Assuming $S = S(P, V)$ and taking into consideration that,

$$\left(\frac{\partial S}{\partial T}\right)_V = \frac{C_V}{T} \quad \text{and} \quad \left(\frac{\partial S}{\partial T}\right)_P = \frac{C_P}{T}$$

Prove that

$$\mathrm{d}S = \frac{C_V}{T}\left(\frac{\partial T}{\partial P}\right)_V \mathrm{d}P + \frac{C_P}{T}\left(\frac{\partial T}{\partial V}\right)_P \mathrm{d}V$$

[8 marks]

**Solution:**
*As entropy is expressed as a function of pressure and molar volume, we can write*
**[2/8]**    *it in differenctial form as,*

$$dS = \left(\frac{\partial S}{\partial P}\right)_V dP + \left(\frac{\partial S}{\partial V}\right)_p dV$$
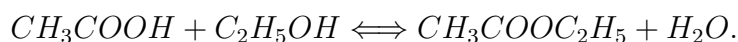
**[3/8]**    *We can rewrite this equation as*

$$dS = \left(\frac{\partial S}{\partial T}\right)_V \left(\frac{\partial T}{\partial P}\right)_V dP + \left(\frac{\partial S}{\partial T}\right)_p \left(\frac{\partial T}{\partial V}\right)_p dV$$

**[3/8]**    *As* $\left(\frac{\partial S}{\partial T}\right)_V = \frac{C_v}{T}$ *and* $\left(\frac{\partial S}{\partial T}\right)_P = \frac{C_P}{T}$,

$$dS = \frac{C_v}{T}\left(\frac{\partial T}{\partial P}\right)_V dP + \frac{C_P}{T}\left(\frac{\partial T}{\partial V}\right)_p dV$$

(b) The liquid phase esterification of acetic acid with ethanol is given by,

$$CH_3COOH + C_2H_5OH \Longleftrightarrow CH_3COOC_2H_5 + H_2O.$$

Calculate the equilibrium mole fraction of ethyl acetate at 100°C, given that initially there were 1 mole of acetic acid and 1 mole of ethanol. The standard enthalpy and Gibbs free energy of the reaction at 25°C are -3.64 kJ.mol$^{-1}$ and -4.65 kJ.mol$^{-1}$, respectively. The van't Hoff equation is given by         [12 marks]

$$\frac{d}{dT}(\ln K) = -\frac{\Delta H^o_{298}}{RT^2}.$$

**Solution:**
*Initially we have 1 mol of acetic acid (HAc) and 1 mol of ethanol (EtOH). We can calculate the mole fractions for all species as a function of the reaction coordinate,*
**[4/12]**    $\epsilon$

$$x_{EtAc} = \frac{\epsilon}{2 + 0.\epsilon} = \frac{\epsilon}{2} = x_{H_2O}$$

$$x_{HAc} = \frac{1 - \epsilon}{2} = x_{EtOH}$$

**[2/12]**   *Assuming ideal solution,*

$$\prod_{i=1}^{c=4} x_i^{\nu} = K = x_{HAc}^{-1} \, x_{EtOH}^{-1} \, x_{EtAc} \, x_{H_2O} \implies K = \frac{\epsilon^2}{\left(1 - \epsilon\right)^2}$$

**[2/12]**   *Thus, by calculating $K$, we can obtain $\epsilon$ and then $x_{EtAc}$. $K$ (temperature-dependent) can be obtained from the Gibbs free energy,*

$$\ln K_{298} = -\frac{\Delta G_{298}^o}{RT} = \frac{4650.0}{8.314 \times 298.15} = 1.8759 \implies K_{298} = 6.5267$$

**[2/12]**   *Now, in order to calculate $K$ at 373.15 K, we can integrate the van't Hoff equation from 298.15 K to 373.15 K*

$$\int_{K_{298}}^{K_{373}} d\left(\ln K\right) = -\int_{298.15}^{373.15} \frac{\Delta H_{298}^o}{RT^2} dT$$

$$\ln\left(\frac{K_{373}}{K_{298}}\right) = -\frac{-3640.0}{8.314}\left(\frac{1}{373.15} - \frac{1}{298.15}\right) \implies K_{373} = 4.8586$$

*Now we can calculate the reaction coordinate,*

$$K_{373} = \frac{\epsilon^2}{\left(1 - \epsilon\right)^2} \implies \epsilon = 0.6879$$

**[2/12]**   *Thus*

$$x_{EtAc} = \frac{\epsilon}{2} = 0.3440$$

**Total Question Marks:20**

**Q.2**    **Question 2**

(a) Show that the van der Waals equation of state (vdW EOS),

$$P = \frac{RT}{V-b} - \frac{a}{V^2}$$

can be expressed as a cubic polynomial equation in $Z$ (compressibility coefficient),

$$Z^3 - (1+B)Z^2 + AZ - AB = 0$$

with $B = bP/(RT)$ and $A = aP/(RT)^2$.                 [7 marks]

**Solution:**

**[2/7]**   *We can rearrange the vdW EOS,*

$$P = \frac{RT}{V-b} - \frac{a}{V^2} \implies \frac{PV}{RT} = \frac{V}{V-b} - \frac{a}{RTV} = \frac{1}{1-\dfrac{b}{V}} - \frac{a}{RTV}$$

**[1/7]**   *Eliminating $V$ as $V = ZRT/P$,*

$$Z = \left(1 - \frac{bP}{ZRT}\right)^{-1} - \frac{aP}{Z(RT)^2} = \frac{ZRT}{ZRT - bP} - \frac{aP}{Z(RT)^2}$$

**[3/7]**   *Manipulating this expression,*

$$Z^2 R^2 T^2 (ZRT - bP) = Z^2 (RT)^3 - aP(ZRT - bP)$$

$$Z^3 - \frac{bP}{RT}Z^2 - Z^2 - \frac{aP}{(RT)^2}Z + ab\frac{P^2}{(RT)^3} = 0$$

**[1/7]**   *with $B = bP/(RT)$, $A = aP/(RT)^2$ and $AB = ab\dfrac{P^2}{(RT)^3}$,*

$$Z^3 - (1+B)Z^2 + AZ - AB = 0$$

(b) Calculate the fugacity of gaseous $CO_2$ at 310 K and $1.4 \times 10^6$ Pa using the van der Waals equation of state (EOS), with $a = 0.3658$ Pa.m$^6$/mol$^2$, $b = 4.286 \times 10^{-5}$ m$^3$/mol. Given,                       [13 marks]

$$\ln\left(\frac{f}{P}\right) = -\ln\left(1 - \frac{b}{V}\right) - \frac{a}{RTV} - \ln Z + (Z-1).$$

Use the largest real root of the cubic polynomial in $Z$ to represent the gaseous phase.

**Solution:**

**[5/13]** *Solving the cubic polynomial in $Z$, with $B = bP/(RT)$ and $A = aP/(RT)^2$,*

$$Z^3 - (1+B)Z^2 + AZ - AB = 0 \implies A = 7.7095 \times 10^{-2} \; ; \; B = 2.3281 \times 10^{-2}$$
$$\implies Z = 0.9436$$

*Now for the fugacity equation, either*

$$\ln\left(\frac{f}{P}\right) = -\ln\left(1 - \frac{b}{V}\right) - \frac{a}{RTV} - \ln Z + (Z-1)$$
*or*
$$\ln\left(\frac{f}{P}\right) = -\ln\left(1 - \frac{B}{Z}\right) - \frac{A}{Z} - \ln Z + (Z-1)$$

**[8/13]** *leads to $f = 1.32 \times 10^6$ Pa.*

**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 isothermically lowering the pressure to 1.013 bar. Calculate the relative amounts of vapour and liquid in equilibrium and their compositions.                    [20 marks]
**Solution:**

**[3/20]** *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,* $P_{C_7}^{sat}$ *= 0.389 bar. Assuming ideal solution,*

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

**[3/20]** *Thus* $K_{C_5}$ *= 2.6861,* $K_{C_6}$ *= 1.0109 and* $K_{C_7}$ *= 0.3840 , therefore*

**[2/20]**
$$y_{C_5} = x_{C_5} K_{C_5}, \;\; y_{C_6} = x_{C_6} K_{C_6}, \;\; y_{C_7} = x_{C_7} K_{C_7}$$

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

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

**[1/20]** *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*
**[3/20]** *expression in* $L$*,*

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

**[2/20]** *Solving this equation leads to* $L = 0.5748$ *and* $V = 0.4252$ *. Calculating the molar*
**[6/20]** *fractions of the species:*

|        | n-C$_5$ | n-C$_6$ | n-C$_7$ |
|--------|---------|---------|---------|
| **x**$_i$ | 0.1456  | 0.4479  | 0.4065  |
| **y**$_i$ | 0.3911  | 0.4528  | 0.1561  |

For this problem, use

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

with [P] = bar, [T] = K and [B$_i$] = J.mol$^{-1}$ and

$$A_{nC_5} = 10.422 \quad A_{nC_6} = 10.456 \quad A_{nC_7} = 11.431$$
$$B_{nC_5} = 26799 \quad B_{nC_6} = 29676 \quad B_{nC_7} = 35200$$

**Total Question Marks:20**

**Q.4** | **Question 4**

(a) A process stream contains light species 1 and heavy species 2. A relatively pure liquid stream containing mostly 2 is obtained through a single-stage liquid/vapour separator. Equilibrium mole fractions are $x_1$ = 0.002 and $y_1$ = 0.950. Assuming that the modified Raoult's law applies,

$$y_i P = x_i \gamma_i P_i^{\text{sat}},$$

determine $T$ and $P$ for the separator. The activity coefficients for the liquid phase are given by,

$$\ln \gamma_1 = 0.93 x_2^2 \quad \text{and} \quad \ln \gamma_2 = 0.93 x_1^2,$$

and the saturated vapour pressure is given by,

$$\ln P^{\text{sat}} = A - \frac{B}{T} \quad \text{with [P] = bar and [T] = [B] = K,}$$

with $A_1$ = 10.08, $B_1$ = 2572.0, $A_2$ = 11.63 and $B_2$ = 6254.0.                [13 marks]

**Solution:**
*Given,*

$$x_1 = 0.002 \implies x_2 = 0.998$$
$$y_1 = 0.950 \implies y_2 = 0.050$$

**[2/13]** | *Calculating the activity coefficient, ,*

$$\ln \gamma_1 = 0.93 x_2^2 \implies \gamma_1 = 2.5251$$
$$\ln \gamma_2 = 0.93 x_1^2 \implies \gamma_2 = 1.0000$$

**[4/13]** | *The modified Raoult's law,*

$$y_i P = x_i \gamma_1 P_i^{sat} \implies P = \frac{x_i \gamma_i P_i^{sat}}{y_i}$$

$$\frac{P_1^{sat}}{P_2^{sat}} = \frac{x_2 \gamma_2 y_1}{x_1 \gamma_1 y_2} = 3754.7028 = \frac{\exp\left(A_1 - \frac{B_1}{T}\right)}{\exp\left(A_2 - \frac{B_2}{T}\right)}$$

**[3/13]** | *Solving this equation results in $T = 376.45$ K . The pressure can now be obtained,*

**[4/13]**

$$P = \frac{x_i \gamma_1 P_1^{sat}}{y_1} = 0.1368 \text{ bar}$$

(b) Determine the temperature and composition of the first bubble created from a saturated liquid mixture of benzene and toluene containing 45 mol% percent of benzene at 200 kPa. Benzene and toluene mixtures may be considered as ideal. Given, [7 marks]

$$\ln P^{sat} = A - \frac{B}{T + C} \quad \text{with [P] = kPa and [T] = [B] = [C] = K,}$$

and

|         | A       | B       | C        |
|---------|---------|---------|----------|
| Benzene | 14.1603 | 2948.78 | -44.5633 |
| Toluene | 14.2514 | 3242.38 | -47.1806 |

**Solution:**
*From Raoult's law,*

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

**[1/7]** *with benzene (1) and toluene (2),*

$$P = x_1 P_1^{sat} + x_2 P_2^{sat}$$

**[3/7]** *leading to the bubble point temperature of the mixture benzene-toluene*

$$P = x_1 \exp\left(A_1 - \frac{B_1}{T + C_1}\right) + x_2 \exp\left(A_2 - \frac{B_2}{T + C_2}\right) \implies T = 391.73 \ K$$

*Calculating the saturation pressure and mole fraction of benzene in the vapour*
**[3/7]** *phase,*

$$P_1^{sat} = \exp\left(A_1 - \frac{B_1}{T - C_1}\right) = 289.01 \ kPa$$

$$y_1 = \frac{x_1 P_1^{sat}}{P} = 0.6503 \ \text{and} \ y_2 = 1 - y_1 = 0.3497$$

**Total Question Marks:20**

**Q.5** | **Question 5**

The molar volume $\left(\text{in cm}^3.\text{mol}^{-1}\right)$ of a binary liquid mixture at $T$ and $P$ is given by:

$$V = 120x_1 + 70x_2 + (15x_1 + 8x_2)\, x_1 x_2$$

(a) Find expressions for the partial molar volumes of species 1 and 2 at $T$ and $P$.

[7 marks]

**Solution:**

[1/7] *Eliminating $x_2 = 1 - x_1$ in the molar volume expression,*

$$\begin{aligned} V &= 120x_1 + 70x_2 + (15x_1 + 8x_2)\, x_1 x_2 \\ &= 70 + 58x_1 - x_1^2 - 7x_1^3 \end{aligned}$$

*The Gibbs-Duhen equation at constant $T$ and $P$ can be expressed as,*

$$\overline{M}_1 = M + x_2 \frac{dM}{dx_1} \ \text{ and } \ \overline{M}_2 = M - x_1 \frac{dM}{dx_1}$$

[2/7] *and are used to obtain $\overline{V}_1$ and $\overline{V}_2$. However we first need to calculate*

$$\frac{dV}{dx_1} = 58 - 2x_1 - 21x_1^2$$

[4/7] *Thus*

$$\begin{aligned} \overline{V}_1 &= 128 - 2x_1 - 20x_1^2 + 14x_1^3 \\ \overline{V}_2 &= 70 + x_1^2 + 14x_1^3 \end{aligned}$$

(b) Show that these expressions satisfy the Gibbs-Duhem equation, $\sum_i x_i d\overline{M}_i = 0$, where $M$ is an intensive thermodynamic property.

[5 marks]

**Solution:**

[1/5] *From this relation,*

$$x_1 d\overline{V}_1 + x_2 d\overline{V}_2 = 0 \ \implies \ x_1 \frac{d\overline{V}_1}{dx_1} + x_2 \frac{d\overline{V}_2}{dx_1} = 0$$

[2/5] *Differentiating $\overline{V}_i$ with repect to $x_1$,*

$$\frac{d\overline{V}_1}{dx_1} = -2 - 40x_1 + 42x_1^2 \ \text{ and } \ \frac{d\overline{V}_2}{dx_1} = 2x_1 + 42x_1^2$$

[2/5] *Now applying it into the original equation,*

$$\begin{aligned} x_1 \left(-2 - 40x_1 + 42x_1^2\right) &= (1 - x_1)\left(2x_1 + 42x_1^2\right) \\ 0 &= 0 \end{aligned} \tag{1}$$
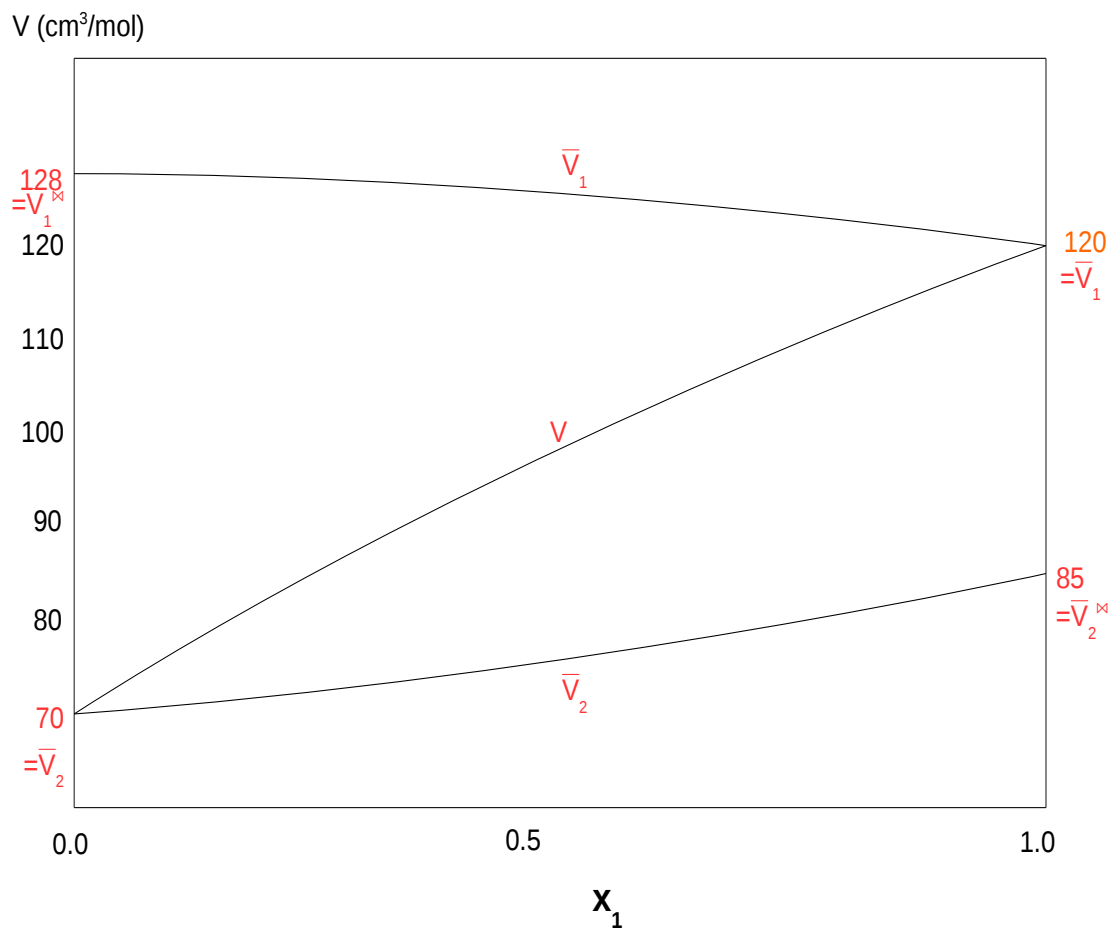
*This demonstrates the validity of the Gibbs-Duhen equation.*

(c) Plot values of $V$, $\overline{V}_1$ and $\overline{V}_2$ calculated by the given equation for $V$ and by the equations developed in (a) *vs* $x_1$. Label points $\overline{V}_1^{\infty}$ and $\overline{V}_2^{\infty}$ and show their values.

[8 marks]

**Solution:**

**[2/8]** *The plot is*

V (cm³/mol)



**[6/8]** *where*

|                    | $x_1 = 0.0$ | $x_1 = 1.0$ |
|--------------------|-------------|-------------|
| $V$                | 70          | 120         |
| $\overline{V}_1$   | 128         | 120         |
| $\overline{V}_2$   | 70          | 85          |

**Total Question Marks:20**

# END OF PAPER

**Total Paper Marks:100**

# List of Equations

- Generic cubic equation of state:

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

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

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

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

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

| **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 | $\alpha_{\mathsf{SRK}}$ | 1 | 0 | 0.08664 | 0.42748 |
| PR | $\alpha_{\mathsf{PR}}$ | $1+\sqrt{2}$ | $1-\sqrt{2}$ | 0.07780 | 0.45724 |

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

- Fundamental thermodynamic equations:

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

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

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

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

- Polytropic Relations:

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

- Raoult's Law:

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

- Henry's Law:

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

- Antoine Equation:

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

- Solutions:

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

# Appendix A: Physical Constants and Conversion Factors

## PHYSICAL CONSTANTS

Avogadro's number, $N_A = 6.023 \times 10^{26}$ molecules/kgmole
Boltzmann's constant, $k = 1.381 \times 10^{-23}$ J/(molecule·K)
Electron charge, $e = 1.602 \times 10^{-19}$ C
Electron mass, $m_e = 9.110 \times 10^{-31}$ kg
Faraday's constant, F = 96,487 kC/kgmole electrons = 96,487 kJ/(V·kgmole electrons)
Gravitational acceleration (standard), $g = 32.174$ ft/s$^2$ = 9.807 m/s$^2$
Gravitational constant, $k_G = 6.67 \times 10^{-11}$ m$^3$/(kg·s$^2$)
Newton's second law constant, $g_c = 32.174$ lbm·ft/(lbf·s$^2$) = 1.0 kg·m/(N·s$^2$)
Planck's constant, $\hbar = 6.626 \times 10^{-34}$ J·s/molecule
Stefan-Boltzmann constant, $\sigma = 0.1714 \times 10^{-8}$ Btu/(h·ft$^2$·R$^4$) = $5.670 \times 10^{-8}$ W/(m$^2$·k$^4$)
Universal gas constant $\Re = 1545.35$ ft·lbf/(lbmole·R) = 8314.3 J/(kgmole·K)
$\qquad\qquad$ = 8.3143 kJ/(kgmole·K) = 1.9858 Btu/(lbmole·R)
$\qquad\qquad$ = 1.9858 kcal/(kgmole·K) = 1.9858 cal/(gmole·K)
$\qquad\qquad$ = 0.08314 bar·m$^3$/(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$^2$ | 1 pascal (Pa) = 1 N/m$^2$ |
| 1 erg = 1 dyne·cm | 1 poundal = 1 lbm·ft/s$^2$ |
| 1 farad (F) = 1 C/V | 1 siemens (S) = 1 A/V |
| 1 henry (H) = 1 Wb/A | 1 slug = 1 lbf·s$^2$/ft |
| 1 hertz (Hz) = 1 cycle/s | 1 tesla (T) = 1 Wb/m$^2$ |
| 1 joule (J) = 1 N·m | 1 volt (V) = 1 W/A |
| 1 lumen = 1 candela·steradian | 1 watt (W) = 1 J/s |
| 1 lux = 1 lumen/m$^2$ | 1 weber (Wb) = 1 V·s |
| 1 newton (N) = 1 kg·m/s$^2$ | |

## CONVERSION FACTORS

| Length | Energy |
|---|---|
| 1 m = 3.2808 ft = 39.37 in = 10$^2$ cm = 10$^{10}$ Å | 1 J = 1 N·m = 1 kg·m$^2$/s$^2$ = $9.479 \times 10^{-4}$ Btu |
| 1 cm = 0.0328 ft = 0.394 in = 10$^{-2}$ m = 10$^8$ Å | 1 kJ = 1000 J = 0.9479 Btu = 238.9 cal |
| 1 mm = 10$^{-3}$ m = 10$^{-1}$ cm | 1 Btu = 1055.0 J = 1.055 kJ = 778.16 ft·lbf = 252 cal |
| 1 km = 1000 m = 0.6215 miles = 3281 ft | 1 cal = 4.186 J = $3.968 \times 10^{-3}$ Btu |
| 1 in = 2.540 cm = 0.0254 m | 1 Cal (in food value) = 1 kcal = 4186 J = 3.968 Btu |
| 1 ft = 12 in = 0.3048 m | 1 erg = 1 dyne·cm = 1 g·cm$^2$/s$^2$ = 10$^{-7}$ J |
| 1 mile = 5280 ft = 1609.36 m = 1.609 km | 1 eV = $1.602 \times 10^{-19}$ J |

*(Continued)*

## CONVERSION FACTORS  (*Continued*)

**Area**

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

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

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

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

**Volume**

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

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

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

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

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

**Mass**

$1\,kg = 1000\,g = 2.2046\,lbm = 0.0685\,slug$

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

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

**Force**

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

$1\,lbf = 4.448\,N = 32.174\,poundals$

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

**Power**

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

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

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

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

**Pressure**

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

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

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

$\qquad = 101.325\,kPa = 760\,mm\,Hg$

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

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

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

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

## MISCELLANEOUS UNIT CONVERSIONS

**Specific Heat Units**

$1\,Btu/(lbm \cdot °F) = 1\,Btu/(lbm \cdot R)$

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

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

**Energy Density Units**

$1\,kJ/kg = 1000\,m^2/s^2 = 0.4299\,Btu/lbm$

$1\,Btu/lbm = 2.326\,kJ/kg = 2326\,m^2/s^2$

**Energy Flux**

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

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

**Heat Transfer Coefficient**

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

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

**Thermal Conductivity**

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

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

**Temperature**

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

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

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

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

**Density**

$1\,lbm/ft^3 = 16.0187\,kg/m^3$

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

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

**Viscosity**

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

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

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

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

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

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

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

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