EN727005

THERMODYNAMICS FOR CHEMICAL ENGINEERS

อุณหพลศาสตร์สำหรับวิศวกรเคมี

Chapter 6

Thermodynamic Properties of fluids

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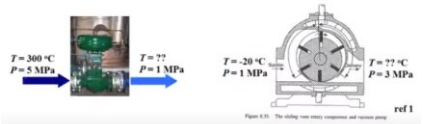
Thermodynamic problems



F(T,P) or F(T,V)

U H S G

6.2 Residual Properties

- The definition for the generic residual property is:

$$M^R \equiv M - M^{ig}$$

M = the Residual Molar gas properties which are at the same temperature and pressure.

M is the actual molar value of any extensive thermodynamics property: V, U, H, S, G.

M^{ig} = the ideal gas properties which are at the same temperature and pressure.

- Residual Gibbs energy:

$$G^R \equiv G - G^{ig}$$

- Residual volume:

$$V^R \equiv V - V^{ig} = V - \frac{RT}{P}$$

PV=ZRT

$$V^R = \frac{RT}{P}(Z-1) \quad \ldots(6.40)$$

Fundamental property relation for residual properties

- The fundamental property relation for residual properties applies to fluids of constant composition.

$$d\left(\frac{G^R}{RT}\right) = \frac{V^R}{RT}dP - \frac{H^R}{RT^2}dT \ldots(6.42)$$

$$\frac{V^R}{RT} = \left[\frac{\partial(G^R/RT)}{\partial P}\right]_T \ldots(6.43)$$

$$\frac{H^R}{RT} = -T\left[\frac{\partial(G^R/RT)}{\partial T}\right]_P \ldots(6.44)$$

$$d\left(\frac{G^R}{RT}\right) = \frac{V^R}{RT}dP - \frac{H^R}{RT^2}dT \ldots(6.42)$$

From Eq.(6.42), $d\left(\frac{G^R}{RT}\right) = \frac{V^R}{RT}dP \quad (const\ T)$

$V^R = \frac{RT}{P}(Z-1) \quad \ldots(6.40)$

Then integrate;

$$\left(\frac{G^R}{RT}\right) = \left(\frac{G^R}{RT}\right)_{P=0} + \int_0^P \frac{V^R}{RT}dP = \int_0^P (Z-1)\frac{dP}{P} \ldots(6.45)$$

$$\left(\frac{G^R}{RT}\right)_{P=0} = 0$$

Diff (6.45) [redacted] put into (6.44) $\frac{H^R}{RT} = -T\left[\frac{\partial(G^R/RT)}{\partial T}\right] \ldots(6.44)$

So, ; $= -T\int_0^P \left(\frac{\partial Z}{\partial T}\right)_P \frac{dP}{P} \ldots(6.46)$

Put (6.45) and (6.46) into (6.47)

From $\frac{S^R}{RT} = \frac{H^R}{RT} - \frac{G^R}{RT} \quad \ldots(6.47)$

So, $\frac{S^R}{R} = -T\int_0^P \left(\frac{\partial Z}{\partial T}\right)_P \frac{dP}{P} - \int_0^P (Z-1)\frac{dP}{P} \quad (const\ T) \quad \ldots(6.48)$

Enthalpy and Entropy from Residual Properties

$G^R \equiv G - G^{ig}$ ⇒ G = G^ig + G^R

$$dH^{ig} = C_P^{ig}\,dT \qquad (6.23)$$

$$dS^{ig} = C_P^{ig}\frac{dT}{T} - R\frac{dP}{P} \qquad (6.24)$$

Applied to H and S; $H = H^{ig} + H^R$ $\qquad S = S^{ig} + S^R$

Integration of Eq. (6.23) ***and*** (6.24);

$$H^{ig} = H_0^{ig} + \int_{T_0}^{T} C_P^{ig}\,dT \qquad S^{ig} = S_0^{ig} + \int_{T_0}^{T} C_P^{ig}\,dT - R\ln\frac{P}{P_0}$$

Substitution; $H = H_0^{ig} + \int_{T_0}^{T} C_P^{ig}\,dT + H^R$ $\qquad \ldots(6.50)$

$$S = S_0^{ig} + \int_{T_0}^{T} C_P^{ig}\,dT - R\ln\frac{P}{P_0} + S^R \qquad \ldots(6.51)$$

$$H^{ig} = H_0^{ig} + \langle C_P \rangle_H (T - T_0) + H^R \qquad \ldots(6.52)$$

$$S^{ig} = S_0^{ig} + \langle C_P \rangle_S \ln\frac{T}{T_0} - R\ln\frac{P}{P_0} + S^R \qquad \ldots(6.53)$$

$$\langle C_P \rangle_H \equiv \frac{\int_{T_1}^{T_2} C_P^{ig}\,dT}{T_2 - T_1} \rightarrow \frac{\langle C_P \rangle_H}{R} = A + BT_{am} + \frac{C}{3}(4T_{am}^2 - T_1T_2) + \frac{D}{T_1T_2}$$

$$\langle C_P \rangle_S \equiv \frac{\int_{T_1}^{T_2} C_P^{ig}\frac{dT}{T}}{\ln(T_2/T_1)} \rightarrow \frac{\langle C_P \rangle_S}{R} = A + BT_{lm} + T_{am}T_{lm}\left[C + \frac{D}{(T_1T_2)^2}\right]$$

The true worth of the Eq. for ideal gases is now evident. They are important because they provide a convenient base for the calculation of real-gas properties.

Practice 2

Calculate H and S of saturated isobutane vapor at 630 K from the following information:

1. Table 6.1 gives compressibility-factor data
2. The vapor pressure of isobutane at 630 K 15.46 bar
3. Set H_0^{ig} = 18,115 Jmol^{-1} and S_0^{ig} = 295.976 Jmol^{-1}K^{-1} for the ideal-gas reference state at 300 K 1 bar
4. $C_p^{ig}/R = 1.7765 + 33.037\times10^{-3}T$ (T/K)

Table 6.1: Compressibility Factors *Z* for Isobutane

P/bar	340 K	350 K	360 K	370 K	380 K
0.10	0.99700	0.99719	0.99737	0.99753	0.99767
0.50	0.98745	0.98830	0.98907	0.98977	0.99040
2	0.95895	0.96206	0.96483	0.96730	0.96953
4	0.92422	0.93069	0.93635	0.94132	0.94574
6	0.88742	0.89816	0.90734	0.91529	0.92223
8	0.84575	0.86218	0.87586	0.88745	0.89743
10	0.79659	0.82117	0.84077	0.85695	0.87061
12	.....	0.77310	0.80103	0.82315	0.84134
14	.....	.....	0.75506	0.78531	0.80923
15.41	.....	.....	0.71727		

Solution 6.3

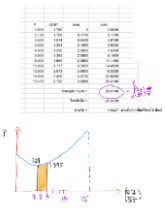
Eqs. ( ) and ( ) are used to calculate H^R and S^R.

$$\int_0^P \left(\frac{\partial Z}{\partial T}\right)_P \frac{dP}{P} \qquad \int_0^P (Z-1)\frac{dP}{P}$$

- Plot $(\partial Z/\partial T)_P/P$ and (Z-1)/P vs. P
- From the compressibility-factor data at 360 K → (Z-1)/P
- The slope of a plot of Z vs. T → $(\partial Z/\partial T)_P/P$
- Data for the required plots are shown in Table 6.2.

Table 6.2: Values of the Integrands Required in Ex. 6.3
Values in parentheses are by extrapolation.

P/bar	$[(\partial Z/\partial T)_P/P] \times 10^4/\text{K}^{-1}\,\text{bar}^{-1}$	$[-(Z-1)/P] \times 10^2/\text{bar}^{-1}$
0	(1.780)	(2.590)
0.10	1.700	2.470
0.50	1.514	2.186
2	1.293	1.759
4	1.290	1.591
6	1.395	1.544
8	1.560	1.552
10	1.777	1.592
12	2.073	1.658
14	2.432	1.750
15.41	(2.720)	(1.835)



$$\int_0^P \left(\frac{\partial Z}{\partial T}\right)_P \frac{dP}{P} = 26.37\times10^{-4}\,K^{-1} \qquad \int_0^P (Z-1)\frac{dP}{P} = -0.2596$$

By Eq. (6.46), $\dfrac{H^R}{RT} = -(360)(26.37\times10^{-4}) = -0.9493$

By Eq. (6.48), $\dfrac{S^R}{R} = -0.9493-(-0.2596) = -0.6897$

For $R = 8.314\ Jmol^{-1}K^{-1}$

$$H^R = (-0.9493)(8.314)(360) = -2{,}841.3\ Jmol^{-1}$$

$$S^R = (-0.6897)(8.314) = 5.734\ Jmol^{-1}K^{-1}$$

$$\frac{\langle C_P^{ig}\rangle_H}{R} = A + BT_{am} = 1.7765 + 33.037\times10^{-3}T_{am}$$

$$\frac{\langle C_P^{ig}\rangle_S}{R} = A + BT_{lm} = 1.7765 + 33.037\times10^{-3}T_{lm}$$

$$T_{am} = \frac{T_0+T_1}{2} = \frac{300+360}{2} = 330\ K$$

$$T_{lm} = \frac{T_1-T_0}{ln(T_1/T_0)} = \frac{360-300}{ln(360/300)} = 329.09\ K$$

$$\langle C_P^{ig}\rangle_H = 12.679(8.314) = 105.41\ Jmol^{-1}K^{-1}$$

$$\langle C_P^{ig}\rangle_S = 12.649(8.314) = 105.16\ Jmol^{-1}K^{-1}$$

Substitute into Eq.(6.50) and (6.51)

$$H = 18{,}115 + 105.41(360-300) - 2{,}841.2 = 21{,}598.5\ Jmol^{-1}$$

$$S = 295.576 + \left[105.16\,ln\left(\frac{360}{300}\right)\right] - [8.314\,ln\,15.41] - 5.734 = 286.676\ Jmol^{-1}K^{-1}$$

6.3 Residual Properties by Equations of State

Residual Properties from the Virial Equation of State

- The two-term virial eq. gives Z-1 = BP/RT.

$$\frac{G^R}{RT} = \int_0^P (Z-1)\frac{dP}{P} \quad \ldots(6.45)$$

So, $\dfrac{G^R}{RT} = \dfrac{BP}{RT} \quad \ldots(6.54)$

By Eq.(6.44), $\dfrac{H^R}{RT} = -T\left[\dfrac{\partial(G^R/RT)}{\partial T}\right]_P = \dfrac{P}{R}\left(\dfrac{B}{T} - \dfrac{dB}{dT}\right) \quad \ldots(6.55)$

Substitution int *o Eq.*(6.47), $\dfrac{S^R}{R} = -\dfrac{P}{R}\dfrac{dB}{dT} \quad \ldots(6.56)$

In application ρ is a more convenient variable than V, PV = ZRT is written in the alternative form.

$$P = Z\rho RT \ldots [redacted] \qquad dP = RT(Zd\rho + \rho dZ) \Rightarrow \frac{dP}{P} = \frac{d\rho}{\rho} + \frac{dZ}{Z}$$

Substitue into Eq.(6.45); $\dfrac{G^R}{RT} = \int_0^\rho (Z-1)\dfrac{d\rho}{\rho} + Z - 1 - ln\,Z \ldots [redacted]$

From Eq.(6.40) and (6.42), $\dfrac{H^R}{RT^2} = \dfrac{Z-1}{P}\left(\dfrac{\partial P}{\partial T}\right)_\rho - \left[\dfrac{\partial(G^R/RT)}{\partial T}\right]_\rho$

Differentition of Eq.(6.57) and (6.58); $\dfrac{H^R}{RT} = -T\int_0^\rho \left(\dfrac{\partial Z}{\partial T}\right)_\rho \dfrac{d\rho}{\rho} + Z - 1 \quad \ldots(6.59)$

From Eq.(6.47), $\dfrac{S^R}{R} = \ln Z - T\int_0^\rho \left(\dfrac{\partial Z}{\partial T}\right)_\rho \dfrac{d\rho}{\rho} - \int_0^\rho (Z-1)\dfrac{d\rho}{\rho} \quad \ldots(6.60)$

- The three-term virial equation.

$$Z - 1 = B\rho + C\rho^2 \quad \textit{is substituted} \text{ int } o \textit{ Eq.}(6.58) \textit{ through } (6.60).$$

$$\Rightarrow \frac{G^R}{RT} = 2B\rho + \frac{3}{2}C\rho^2 - \ln Z \quad \ldots(6.61)$$

$$\frac{H^R}{RT} = T\left[\left(\frac{B}{T} - \frac{dB}{dT}\right)\rho + \left(\frac{C}{T} - \frac{1}{2}\frac{dC}{dT}\right)\rho^2\right] \quad \ldots(6.62)$$

$$\frac{S^R}{R} = \ln Z - T\left[\left(\frac{B}{T} + \frac{dB}{dT}\right)\rho + \frac{1}{2}\left(\frac{C}{T} - \frac{dC}{dT}\right)\rho^2\right] \ldots(6.63)$$

Application of these equations, useful for gases up to moderate pressure, requires data for both the second and third virial coefficients.

Residual Properties by Cubic Equations of State

Eq.(3.42) devides by ρRT and substitut e $V = 1/\rho$, as q given by *Eq.*(3.51).

$$\Rightarrow \quad Z = \frac{1}{1-\rho b} - q\frac{\rho b}{(1+\varepsilon\rho b)(1+\sigma\rho b)}$$

$$Z - 1 = \frac{\rho b}{1-\rho b} - q\frac{\rho b}{(1+\varepsilon\rho b)(1+\sigma\rho b)} \quad \ldots(6.64)$$

$$\left(\frac{\partial Z}{\partial T}\right)_\rho = -\left(\frac{dq}{dT}\right)\frac{\rho b}{(1+\varepsilon\rho b)(1+\sigma\rho b)}$$

The integrals of Eqs.(6.58), (6.60);

$$\int_0^\rho (Z-1)\frac{d\rho}{\rho} = \int_0^\rho \frac{\rho b}{1-\rho b}\frac{d(\rho b)}{\rho b} - q\int_0^\rho \frac{d(\rho b)}{(1+\varepsilon\rho b)(1+\sigma\rho b)}$$

$$\int_0^\rho \left(\frac{\partial Z}{\partial T}\right)_\rho \frac{d\rho}{\rho} = -\frac{dq}{dT}\int_0^\rho \frac{d(\rho b)}{(1+\varepsilon\rho b)(1+\sigma\rho b)}$$

To simplify; $\int_0^\rho (Z-1)\dfrac{d\rho}{\rho} = -\ln(1-\rho b) - qI,$ There are 2 cases of I

The generic equation of state presents two cases.

Case I: $\varepsilon \neq \sigma \quad I = \dfrac{1}{\sigma - \varepsilon} \ln\left(\dfrac{1+\sigma\rho b}{1+\varepsilon\rho b}\right)$ …(6.65a)

When ρ is eliminated in favor of Z.

$\beta = \dfrac{bP}{RT} \qquad Z = \dfrac{P}{\rho RT} \qquad whence \quad \dfrac{\beta}{Z} = \rho b$

$I = \dfrac{1}{\sigma - \varepsilon} \ln\left(\dfrac{Z+\sigma\beta}{Z+\varepsilon\beta}\right)$ …(6.65b)

Case II: $\varepsilon = \sigma \quad I = \dfrac{\rho b}{1+\varepsilon\rho b} = \dfrac{\beta}{Z+\varepsilon\beta}$

Case II: $\varepsilon = \sigma \quad I = \dfrac{\rho b}{1+\varepsilon\rho b} = \dfrac{\beta}{Z+\varepsilon\beta}$

$\dfrac{G^R}{RT} = Z - 1 - \ln(1-\rho b)Z - qI$ …(6.66a)

$\dfrac{G^R}{RT} = Z - 1 - \ln(Z-\beta)Z - qI$ …(6.66b)

$\dfrac{H^R}{RT} = Z - 1 + \left[\dfrac{d\ln\alpha(T_r)}{d\ln T_r} - 1\right] qI$ …(6.67)

$\dfrac{S^R}{R} = \ln(Z-\beta) + \dfrac{d\ln\alpha(T_r)}{d\ln T_r} qI$ …(6.68)

Ex. 6.4

Find values for the H^R and S^R for n-butane gas at 500 K 50 bar as given by the Redlich/Kwong Eequation.

Solution

T_r = 500/425.1 = 1.176, P_r = 50/37.96 = 1.317

From Table 3.1:

$Eq.(3.53);\ \beta = \Omega\dfrac{P_r}{T_r} = 0.08664\dfrac{1.317}{1.176} = 0.09703$

$Eq.(3.54);\ q = \dfrac{\Psi\alpha(T_r)}{\Omega T_r} = \dfrac{0.42748}{(0.08664)(1.176)^{3/2}} = 3.8689$

Table 3.1: Parameter Assignments for Equations of State

For use with Eqs. (3.49) through (3.56)

Eq. of State	$\alpha(T_r)$	σ	ϵ	Ω	Ψ	Z_c
vdW (1873)	1	0	0	1/8	27/64	3/8
RK (1949)	$T_r^{-1/2}$	1	0			1/3
SRK (1972)	$\alpha_{SRK}(T_r;\omega)^\dagger$	1	0			1/3
PR (1976)	$\alpha_{PR}(T_r;\omega)^\ddagger$	$1+\sqrt{2}$	$1-\sqrt{2}$	0.07780	0.45724	0.30740

$^\dagger\alpha_{SRK}(T_r;\omega) = \left[1 + (0.480 + 1.574\,\omega - 0.176\,\omega^2)\left(1 - T_r^{1/2}\right)\right]^2$

$^\ddagger\alpha_{PR}(T_r;\omega) = \left[1 + (0.37464 + 1.54226\,\omega - 0.26992\,\omega^2)\left(1 - T_r^{1/2}\right)\right]^2$

$Eq.(3.52):\ Z = 1 + \beta - q\beta\dfrac{Z-\beta}{(Z+\varepsilon\beta)(Z+\sigma\beta)}$

$= 1 + 0.09703 - (3.8689)(0.09703)\dfrac{Z - 0.09703}{Z(Z+0.09703)}$

Solution of this Eq. yields $Z = 0.6850$. *Then:*

$I = \ln\dfrac{Z+\beta}{Z} = 0.13247$

With $\ln\alpha(T_r) = -\dfrac{1}{2}\ln T_r, \quad d\ln\alpha(T_r)/d\ln T_r = -\dfrac{1}{2}$. *Then:*

$Eq.(6.67):\ \dfrac{H^R}{RT} = 0.6850 - 1 + (-0.5-1)(3.8689)(0.13247) = -1.0838$

$Eq.(6.68):\ \dfrac{S^R}{R} = \ln(0.6850 - 0.09703) - [0.5(3.8689)0.13247] = -0.78735$

Thus, $H^R = 8.314(500)(-1.0838) =$ [redacted]

$S^R = 8.314(-0.78735) = -6.546\ Jmol^{-1}K^{-1}$

These results are compared with those of other calculation in Table 6.3.

Table 6.3: Values for Z, H^R, and S^R for n-Butane at 500 K and 50 bar

Method	Z	H^R/J mol^{-1}	S^R/J mol^{-1}K^{-1}
vdW Eqn.	0.6608	−3,937	−5.424
RK Eqn.	0.6850	−4,505	−6.546
SRK Eqn.	0.7222	−4,824	−7.413
PR Eqn.	0.6907	−4,988	−7.426
Lee/Kesler†	0.6988	−4,966	−7.632
Handbook‡	0.7060	−4,760	−7.170

† Described in Sec. 6.7.

‡ Values derived from numbers in Table 2–240, p. 2–223, *Chemical Engineers' Handbook*, 7th ed., Don Green (ed.), McGraw-Hill, New York, 1997.

6.4 TWO-PHASE SYSTEMS

$G^{\alpha} = G^{\beta}, \quad dG^{\alpha} = dG^{\beta} \rightarrow V^{\alpha} dP^{sat} - S^{\alpha} dT = V^{\beta} dP^{sat} - S^{\beta} dT$

Rearrangement, $\dfrac{dP^{sat}}{dT} = \dfrac{S^{\beta} - S^{\alpha}}{V^{\beta} - V^{\alpha}} = \dfrac{\Delta S^{\alpha\beta}}{\Delta V^{\alpha\beta}}$

Integration of Eq.(6.8); $\Delta H^{\alpha\beta} = T\Delta S^{\alpha\beta}$ *(The latent heat of phase transition)*

Thus, $\Delta S^{\alpha\beta} = \Delta H^{\alpha\beta} / T \Rightarrow \dfrac{dP^{sat}}{dT} = \dfrac{\Delta H^{\alpha\beta}}{T\Delta V^{\alpha\beta}} \ldots(6.71)$ *: The Clapeyron equation*

Phase transition from liquid to vapor; $\dfrac{dP^{sat}}{dT} = \dfrac{\Delta H^{lv}}{T\Delta V^{lv}} \ldots(6.72)$

But $\Delta V^{lv} = \dfrac{RT}{P^{sat}} \Delta Z^{lv} \Rightarrow \dfrac{d \ln P^{sat}}{dT} = \dfrac{\Delta H^{lv}}{RT^2 \Delta Z^{lv}} \ldots(6.73)$

or $\dfrac{d \ln P^{sat}}{d(1/T)} = \dfrac{\Delta H^{lv}}{R\Delta Z^{lv}} \ldots(6.74)$

} The Clapeyron eq. for pure-species vaporization

Temperature Dependence of the Vapor Pressure of Liquids

$$\ln P^{sat} = A - \frac{B}{T}$$

The Antoine eq.: $\ln P^{sat} = A - \dfrac{B}{T + C} \ldots(6.76)$

Antoine constants are given in Table B.2, App.B

A function of T_r*;* $\ln P_r^{sat}(T_r) = \dfrac{A\tau + B\tau^{1.5} + C\tau^3 + D\tau^6}{1 - \tau} \ldots(6.77)$

where $\tau \equiv 1 - T_r$

Corresponding-States Correlations for Vapor Pressure

Lee / Kesler correlation:

$$\ln P_r^{sat}(T_r) = \ln P_r^0(T_r) + \omega \ln P_r^1(T_r) \ldots(6.78)$$

where $\ln P_r^0(T_r) = 5.92714 - \dfrac{6.09648}{T_r} - 1.28862 \ln T_r + 0.169347 T_r^6 \ldots(6.79)$

$$\ln P_r^1(T_r) = 15.2518 - \frac{15.6875}{T_r} - 13.4721 \ln T_r + 0.43577 T_r^6 \ldots(6.80)$$

$$\omega = \frac{\ln P_{r_n}^{sat} - \ln P_r^0(T_{r_n})}{\ln P_r^1(T_{r_n})} \ldots(6.81)$$

where

T_{r_n} : The reduced normal boiling point

$P_{r_n}^{sat}$: The reduced vapor pressure corresponding to 1 atm

Ex. 6.6

Determine the vapor pressure for liquid n-hexane at 0, 30, 60 and 90°C: (a) With constants from Apendix B.2.
(b) From the Lee/Kesler correlation for P_r^{sat}

Solution

(a) $\ln P^{sat} = 13.8193 - \dfrac{2696.04}{t + 224.317}$

(b) Eq.(6.78);
From Table B.1, $T_{r_n} = \dfrac{341.9}{507.6} = 0.6736, \quad P_{r_n}^{sat} = \dfrac{1.01325}{30.25} = 0.03350$
From Eq.(6.81) → ω =0.298

t/°C	Psat/kPa (Antoine)	Psat/kPa (Lee/Kesler)	t/°C	Psat/kPa (Antoine)	Psat/kPa (Lee/Kesler)
0	6.052	5.835	30	24.98	24.49
60	76.46	76.12	90	189.0	190.0

The average difference from the Antoine values is about 1.5%.

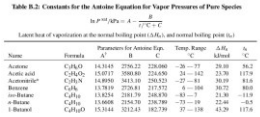


Table B.2: Constants for the Antoine Equation for Vapor Pressures of Pure Species

$$\ln P^{sat}/\text{kPa} = A - \frac{B}{t/°\text{C} + C}$$

Latent heat of vaporization at the normal boiling point (ΔH_n), and normal boiling point (t_n)

Name	Formula	Parameters for Antoine Eqn. A†	B	C	Temp. Range °C	ΔH_n kJ/mol	t_n °C
n-Hexane	C_6H_{14}	13.8193	2696.04	224.317	−19 — 92	28.85	68.7

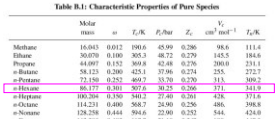


Table B.1: Characteristic Properties of Pure Species

	Molar mass	ω	T_c/K	P_c/bar	Z_c	V_c / cm³ mol⁻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.	491.2
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

Two-Phase Liquid/Vapor System

$$nV = n^l V^l + n^v V^v \qquad n = n^l + n^v \quad (moles)$$

$$V = x^l V^l + x^v V^v \qquad x: \ mass \ fraction$$

$$V = (1 - x^v) V^l + x^v V^v \qquad x^l = 1 - x^v$$

The generic equation:

$$M = (1 - x^v) M^l + x^v M^v \quad \ldots(6.82a)$$

where $M \equiv V, U, H, S, etc.$ *An alternative form:*

$$M = M^l + x^v \Delta M^{lv} \quad \ldots(6.82b)$$

6.5 THERMODYNAMIC DIAGRAMS

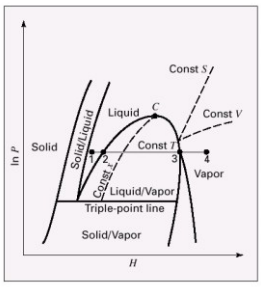


Figure 6.2: PH diagram.

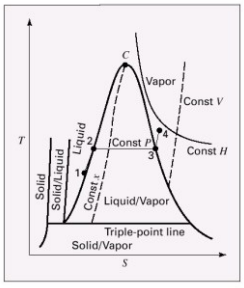


Figure 6.3: TS diagram.

6.6 Tables of Thermo. Properties

End of Part 2