Preparation of Psychrometric Charts for Alcohol Vapours in Nitrogen

David C. Shallcross[†]

Department of Chemical Engineering, The University of Melbourne, Parkville, Victoria 3010, Australia
(*Received 30 September 1999 • accepted 27 October 1999*)

Abstract−Psychrometric charts for three different systems involving condensing alcohol vapour in nitrogen are presented. The alcohols considered are methanol, ethanol and n-propanol. The charts are based upon semi-theoretical equations and make use of published physical property data and correlations. The behaviour of the vapour phase is characterised by the Virial Equation of State truncated at the third term. The solubility of nitrogen in the liquid alcohols is also considered. The charts are constructed with the dry bulb temperature and absolute humidity scales as the orthogonal axes. Curves of constant adiabatic saturation temperature, constant relative humidity, constant gas specific volume and constant enthalpy deviation are plotted on the charts.

Key words: Psychrometry, Humidity, Virial Equation, Alcohol

INTRODUCTION

For any system in which one or more components of a gaseous mixture may condense, engineering requires the ability to predict the conditions and extent to which condensation will occur. Even in this age of computer-aided design and physical property databases, engineers still find it useful to have physical property data presented graphically. Psychrometric charts are a way in which physical property data may be presented diagrammatically for systems in which one component of a gaseous mixture may condense. While accurate charts are readily available for the conventional water-air system, only recently have charts been prepared for other important systems. Just as importantly, until recently [Shallcross, 1997] few charts had been prepared for pressure other than atmospheric.

The author [Shallcross and Low, 1994, 1996; Shallcross, 1997] has described the theory behind the construction of psychrometric charts. In this paper this method will be applied to construct a series of psychrometric charts for alcohol vapours in nitrogen. The alcohols considered are methanol, ethanol and n-propanol.

GAS PHASE BEHAVIOUR AND SATURATION

At even relatively low pressures the gas mixture of nitrogen and the liquid alcohols will not behave ideally. From the many different methods by which the non-ideal behaviour of gas may be characterized, the Virial Equation of State is used. This method is relatively simple to apply and considerable data is available for the required parameters for each of the systems studied. The Virial Equation of State truncated at the third term is:

$$\frac{P_T \hat{V}}{RT} = 1 + \frac{B_m}{\hat{V}} + \frac{C_m}{\hat{V}^2} \tag{1}$$

[†]To whom correspondence should be addressed.
E-mail: d.shallcross@chemeng.unimelb.edu.au
This paper was presented at the 8th APCChE (Asia Pacific Confederation of Chemical Engineering) Congress held at Seoul between August 16 and 19, 1999.

where, P_T is the total pressure, $\hat{V}$ is the molar volume of the gas mixture, R is the gas constant, T is the absolute temperature, and B_m and C_m are the second and third virial coefficients of the gas, respectively.

In the development of the equations which follow we shall assume that there are only two components in our system. The vapour component that readily condenses will be denoted V, and the gas component will be denoted G.

If x_G is the mole fraction of the non-condensing component (in this case nitrogen) and x_V is the mole fraction of the condensing component (i.e., the alcohol), then for a binary system it may be shown that:

$$B_m = x_G^2 B_{GG} + 2x_G x_V B_{GV} + x_V^2 B_{VV} \tag{2}$$

$$C_m = x_G^3 C_{GGG} + 3x_G^2 x_V C_{GGV} + 3x_G x_V^2 C_{GVV} + x_V^3 C_{VVV} \tag{3}$$

Here B_{ii} is the second virial coefficient of pure component i, B_{GV} is the second virial interaction (or cross) coefficient for the binary system, C_{iii} is the third virial coefficient of pure component i, and, C_{GGV} and C_{GVV} are the third virial interaction parameters. The virial coefficients are all functions of temperature alone, and are either known or may be estimated for most binary systems.

A gas is saturated with a vapour when the partial pressure of the vapour is equal to its vapour pressure at the particular temperature. For an ideal system we could write an expression relating the mole fraction of the condensing vapour component at saturation, V, to its vapour pressure:

$$x_{V_s} = \frac{P_V}{P_T} \tag{4}$$

and

$$x_{G_s} = \frac{P_T - P_V}{P_T} \tag{5}$$

where, x_{V_s} and x_{G_s} are the mole fractions of components V and G, respectively, at saturation, and P_V is the vapour pressure of component V. However, since the system is not ideal Hyland and Wexler [1983] proposed the use of an enhancement factor.

Eq. (4) becomes,

$$x_{Vs}=\frac{fP_V}{P_T} \tag{6}$$

A similar expression may be written for the non-condensing gas component G:

$$x_{Gs}=\frac{P_T-fP_V}{P_T} \tag{7}$$

The enhancement factor accounts for the effects of the dissolved gases and pressure on the properties of the condensed phase, and the effect of intermolecular forces on the properties of the moisture itself. Typically, the value for the enhance factor does not exceed 1.05 for any given system [Shallcross, 1996]. The enhancement factor may be written in terms of the virial coefficients and other properties of the system [Hyland and Wexler, 1983]:

$$
\begin{aligned}
\ln f=&\left[\frac{(1+\kappa P_V)(P_T-P_V)-\frac{1}{2}\kappa(P_T^2-P_V^2)}{RT}\right]\hat{V}_{Vc}+\ln(1-k_Hx_{Gs}P_T)\\
&-\frac{2x_{Gs}^3(2-3x_{Gs})P_T^2}{(RT)^2}B_{GG}B_{GV}+\frac{x_{Gs}^2P_T}{RT}B_{GG}-\frac{2x_{Gs}^2P_T}{RT}B_{GV}\\
&-\left[\frac{P_T-P_V-x_{Gs}^2P_T}{RT}\right]B_{GG}-\frac{x_{Gs}^2(1-3x_{Gs})(1-x_{Gs})P_T^2}{(RT)^2}B_{GG}B_{VV}\\
&+\frac{6x_{Gs}^2(1-x_{Gs})^2P_T^2}{(RT)^2}B_{VV}B_{GV}-\frac{2x_{Gs}^2(1-x_{Gs})(1-3x_{Gs})P_T^2}{(RT)^2}B_{GV}^2\\
&-\left[\frac{P_V^2-(1+3x_{Gs})(1-x_{Gs})^3P_T^2}{2(RT)^2}\right]B_{VV}^2-\frac{3x_{Gs}^4P_T^2}{2(RT)^2}B_{GG}^2\\
&+\frac{3x_{Gs}^2(1+2x_{Gs})P_T^2}{2(RT)^2}C_{GGV}-\frac{3x_{Gs}^2(1-x_{Gs})P_T^2}{(RT)^2}C_{GVV}\\
&-\left[\frac{(1+2x_{Gs})(1-x_{Gs})^2P_T^2-P_V^2}{2(RT)^2}\right]C_{VVV}+\frac{x_{Gs}^3P_T^2}{(RT)^2}C_{GGG} \tag{8}
\end{aligned}
$$

Here κ is the iso-thermal compressibility of the condensing component (i.e., the hydrocarbon), V_{Vc} is the molar volume of the condensed component V (either as a liquid or a solid), and k_H is the Henry's Law constant to account for the solubility of component G in the condensed phase. For a given temperature and total pressure, P_T, Eq. (7) and (8) may be solved iteratively for the enhancement factor, f, and the mole fraction of component G at saturation, x_{Gs}. In practice this is done by first setting f=1. x_{Gs} is then calculated by using Eq. (7), and then this value is used in Eq. (8) to calculate an estimate for the enhancement factor, f. The value for x_{Gs} is then recalculated. The cycle is then repeated until the values for f and x_{Gs} no longer change significantly between successive calculations.

The absolute humidity at saturation, H_s, is the mass of the vapour component V per mass of component G. It may be expressed in terms of the mole fractions of the two components in the gas phase at saturation:

$$H_s=\frac{x_{Vs}MW_V}{x_{Gs}MW_G} \tag{9}$$

where MW_i is the molecular weight of component i.

Shallcross and Low [1994] and Shallcross [1997] show how

a psychrometric chart for a system may be calculated using the Virial Equation and the enhancement factor to account for the non-idealities in the system. The psychrometric charts are constructed with temperature plotted on the x-axis and absolute humidity on the orthogonal y-axis. The saturation line that describes the boundary of the humidity chart is drawn by plotting the absolute humidity at saturation, H_s, as a function of temperature for a specified total pressure. Series of curves for constant relative humidity, constant specific volume and constant adiabatic saturation temperature may be generated by use of the equations presented.

The relative humidity, ϕ, is defined as the ratio of the mole fraction of the vapour component, x_V, in a given sample of the two-component mixture to the mole fraction, x_{Vs}, in a sample of the mixture which is saturated with the vapour component at that temperature. Thus,

$$\phi=\frac{x_V}{x_{Vs}} \tag{10}$$

In order to construct the curves of constant relative humidity an expression is required which relates the absolute humidity to the relative humidity, temperature and total pressure. Shallcross [1997] derives the equation:

$$H=\frac{H_s\phi(1-fP_V/P_T)}{1-\phi fP_V/P_T} \tag{11}$$

To construct the constant relative humidity curves, the system pressure, P_T, is first specified. Then for a given value of ϕ, the variables f, H_s and P_v are calculated for varying temperatures. These values are then used in Eq. (11) to calculate the absolute humidity as a function of temperature. When plotted, this data yields the constant relative humidity curves.

The specific volume of a humid mixture, ν, is defined as the volume of the mixture per unit mass of the dry gas:

$$\nu=\frac{\hat{V}}{x_GMW_G} \tag{12}$$

Applying this definition and using Eq. (1), Shallcross [1997] shows how the curves of constant specific volume may be plotted for a given system pressure.

The wet bulb temperature is usually considered as the temperature measured by a cylindrical thermometer, the outside surface of which is kept wet with the liquid of the condensing component V. As the moist gas passes the thermometer some of the liquid evaporates resulting in a cooling effect that causes the temperature of the wet bulb thermometer to drop. The drier the gas, the greater the wet bulb depression. It is not possible to predict the wet bulb temperatures with precision, because the wet bulb temperature is a function of not only the dry bulb temperature and absolute humidity, but also such factors as the gas velocity past the thermometer, the diameter of the thermometer and the extent of radiative heat transfer. Consequently, we instead choose to plot curves of constant adiabatic saturation temperature. However, for the air-water system the curves of constant adiabatic saturation temperature coincide with curves of constant wet bulb temperature. This is because for the air-water system the Lewis Number is equal to one.

For the conventional air-water system, ASHRAE [1989] de-

fines the adiabatic saturation temperature, T_{ad}, as the temperature at which water (liquid or solid), by evaporating into moist air at a given dry bulb temperature, T, and absolute humidity, H, can bring air to saturation adiabatically at the same temperature, T_{ad}, while the pressure P_T, is maintained constant. The adiabatic saturation temperature is also known as the thermodynamic wet bulb temperature.

For a given G-V system, it may be defined as the temperature at which component V, present as either a liquid or a solid, by evaporating into the moist gas mixture at a given dry bulb temperature, T, and absolute humidity, H, can bring that mixture to saturation adiabatically at the same temperature, T_{ad}, while the pressure, P_T, is maintained constant. The method used to plot the curves of constant adiabatic saturation temperature is described in detail by Shallcross and Low [1994] and Shallcross [1997].

The calculation and representation of the specific enthalpy of the gas mixture requires special attention. The specific of the two-component gas mixture is calculated by summing the ideal gas state enthalpy and the residual enthalpy:

$$\hat{h}=x_G\left(\hat{h}_{oG}+\int_{T_o}^{T}C_{P_G}dT\right)+x_V\left(\hat{h}_{oV}+\int_{T_o}^{T}C_{P_V}dT\right)$$
$$+RT\left[\left(T\frac{dB_m}{dT}-B_m\right)\frac{1}{\hat{V}_m}+\left(\frac{T}{2}\frac{dC_m}{dT}-C_m\right)\frac{1}{\hat{V}_m^2}\right] \qquad (13)$$

In this equation T_o is the enthalpy datum temperature, C_{PG} and C_{PV} are the ideal gas heat capacity of the gas and vapour, respectively, and, $\hat{h}_{oG}$ and $\hat{h}_{oV}$ are the enthalpy corrections for both components necessary to ensure that the enthalpy, $\hat{h}$, is in fact zero at the enthalpy datum condition.

Because of the nature of the equations governing the construction of the constant adiabatic saturation temperature curves, lines of constant gas mixture enthalpy will lie nearly parallel with the adiabatic saturation temperature curves. Rather than plotting two sets of curves having nearly the same slope, which would result

in a chart difficult to read, the gas mixture enthalpy data is presented in a different form. An enthalpy deviation term, $\hat{h}_{dev}$, is defined as being the difference between the true specific enthalpy of a gas mixture and the specific enthalpy of the gas saturated at its adiabatic saturation temperature:

$$\hat{h}_{dev}=\hat{h}-\hat{h}_{S,as} \qquad (14)$$

When curves of constant enthalpy deviation are plotted on the psychrometric chart, then the true specific enthalpy of a gas mixture can be determined by adding the enthalpy deviation for the point on the chart representing the mixture, to the enthalpy of the gas saturated at its adiabatic saturation temperature.

CHART PREPARATION AND PRODUCTION

Using the equations developed by Shallcross and Low [1994] and Shallcross [1997] together with the relevant physical property data presented in Appendix A, psychrometric charts were prepared for the methanol-nitrogen, ethanol-nitrogen and n-propanol-nitrogen systems. The temperature ranges of each chart are chosen to ensure that the condensing hydrocarbon component is always present as a liquid rather than a solid.

A FORTRAN program was written incorporating the equations and physical property data for each system. These programs generate output files of instructions in the Postscript graphics language. When sent to a suitable Postscript laser printer the psychrometric charts presented in Figs. 1 to 4 are produced. The charts are printed on a printer having a resolution of 600 dots per inch (23.6 dots per mm). This allows the curves on the charts to be plotted with extreme precision. On a chart with a temperature range of 0 to 60 °C a plotting precision of 600 dots per inch is equivalent to placing a line with an accuracy of 0.01 °C.

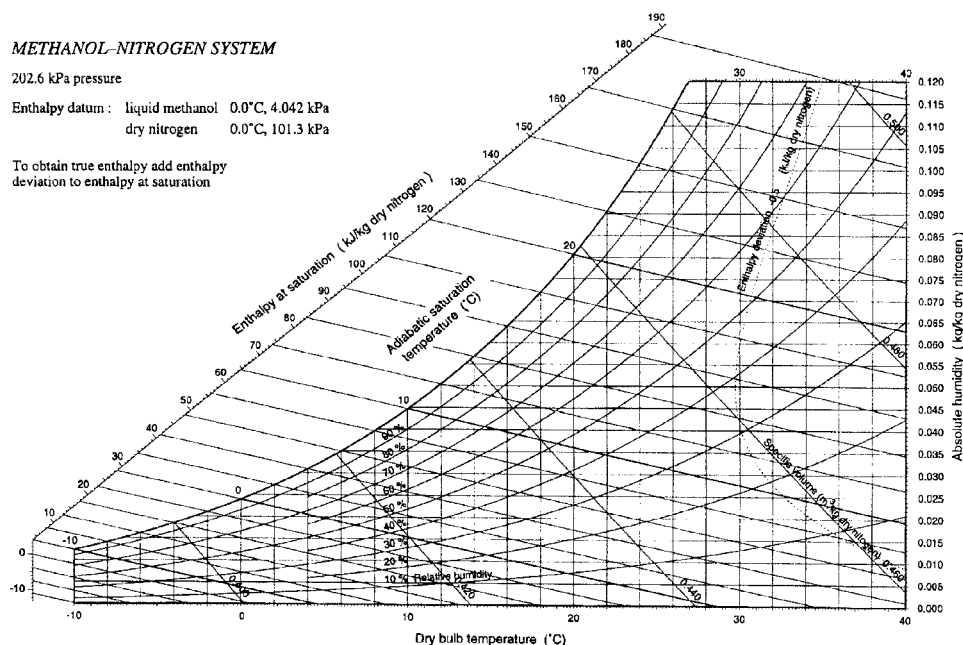The layout of Fig. 1 is typical of the psychrometric chart

Fig. 1. Psychrometric chart for the methanol-nitrogen system at 101.3 kPa.
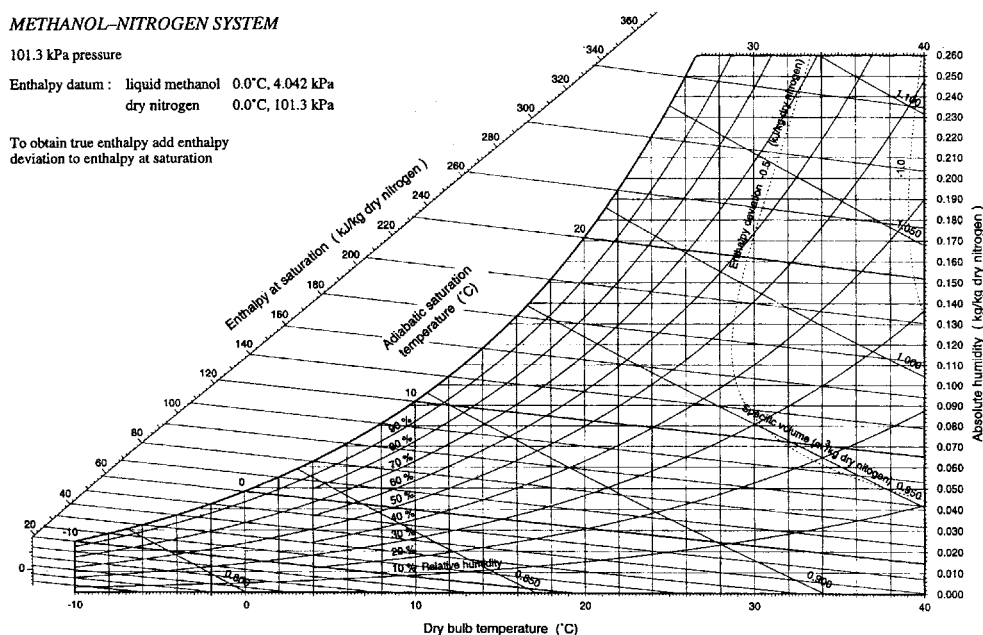
Fig. 2. Psychrometric chart for the methanol-nitrogen system at 202.6 kPa.
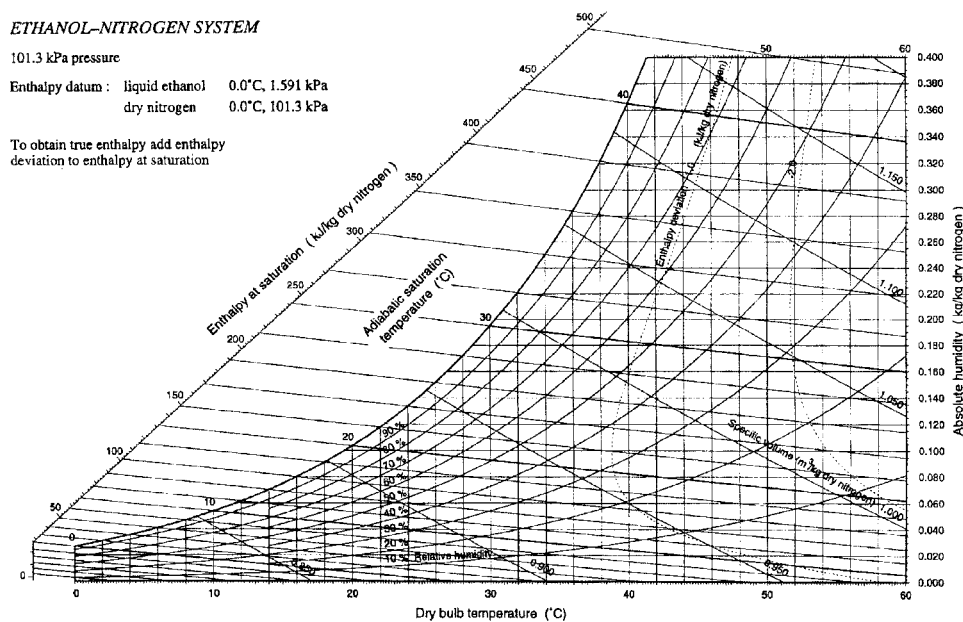

Fig. 3. Psychrometric chart for the ethanol-nitrogen system at 101.3 kPa.

produced by the FORTRAN program. Dry bulb temperature is plotted on the x-axis with absolute humidity plotted on the y-axis. The relative humidity, specific volume, adiabatic saturation temperature and enthalpy deviation curves are all plotted as functions of dry bulb temperature and absolute humidity. The layout of the chart is self-explanatory. The enthalpy datum condition for the methanol is taken as liquid methanol, its vapour pressure at 0 °C.

The inclined scale for the enthalpy at saturation is slightly non-linear with units varying in size along the length of the scale. The scale is prepared by extrapolating the lines of constant adiabatic saturation temperature beyond the saturation curve to inter-

sect the inclined scale. The values of enthalpy at saturation at each adiabatic saturation temperature then form the basis of the scale.

Figs. 1 and 2 present the psychrometric charts for the methanol-nitrogen system at 101.3 kPa and 202.6 kPa, respectively. While the shapes of these two diagrams are similar, the scales on the absolute humidity axis are different, reflecting the fact that the boiling point of methanol increases with increasing pressure. The enthalpy and specific volume scales are also different.

CONCLUDING REMARKS

Using published physical property data and correlations, and
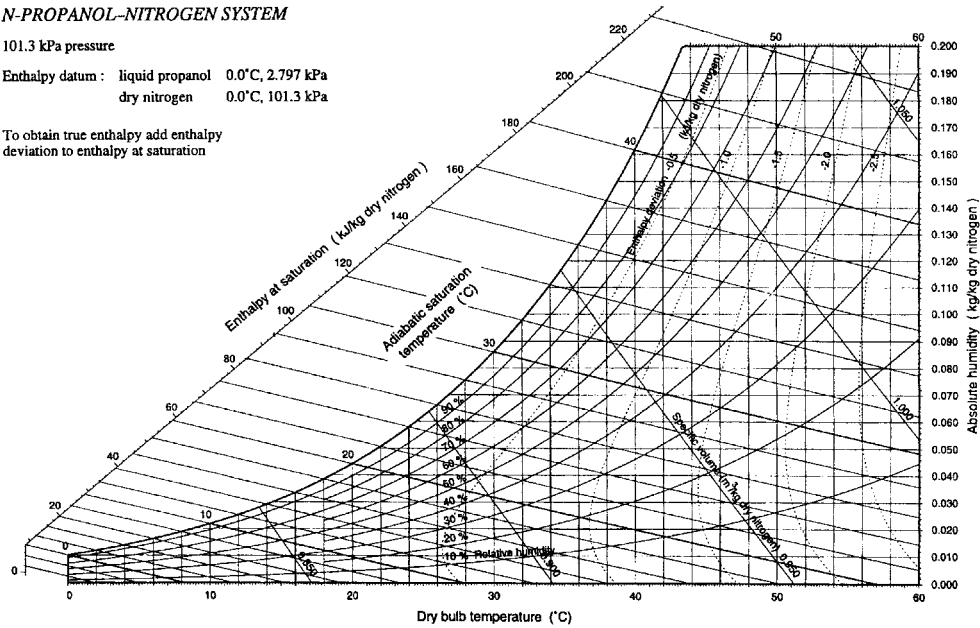
Fig. 4. Psychrometric chart for the n-propanol-nitrogen system at 101.3 kPa.

equations developed earlier by the author, a series of high-precision psychrometric charts have been constructed for three systems involving alcohol vapours and nitrogen. The fact that the model produces a chart in very close agreement to the widely accepted standard psychrometric chart for the water-air system supports the notion that the reliability of the charts produced is high.

APPENDIX A : DATA FOR THE THREE SYSTEMS

1. Molecular Weights, Critical Point and the Acentric Factor Data

A number of the correlations used to estimate the required parameters call for information concerning the molecular weight, critical point and the acentric factor for each component. This information is presented in Table 1.

2. Second Virial Coefficients

Second virial coefficient data for a range of components may be related to temperature by a correlation of the form [Kehiaian, 1995]:

$$B=\sum_{i=1}^{4}c_i\left(\frac{298.15}{T}-1\right)^{i-1} \tag{15}$$

where, T is expressed in Kelvin, and B is expressed in cm^3/mol. Values for the three parameters are tabulated in Table 2.

3. Second Virial Cross Coefficients

Table 1. Molecular weight, critical point and the acentric factor data

Component	MW	T_c(K)	P_c(MPa)	V_c (m^3/kmol)	Z_c	ω
Methanol	32.042	512.64	8.097	0.1178	0.224	0.565
Ethanol	46.069	513.92	6.137	0.1670	0.240	0.637
n-Propanol	60.096	536.78	5.170	0.2185	0.253	0.628
Nitrogen	28.014	126.2	3.3944	0.0895	0.290	0.040

Table 2. Second virial coefficients for Eq. (15)

Component	c_1	c_2	c_3
Methanol	−1752	−4694	
Ethanol	−4475	−29719	−56716
n-Propanol	−2690	−12040	−16738
Nitrogen	−4	−56	12

The second virial cross coefficients are estimated by using the empirical correlation [Pitzer, 1990]:

$$B_{ij}=\hat{V}_{c_{ij}}\left[c_1+\omega_{ij}c_2+\frac{c_3+\omega_{ij}c_4}{T_{r_{ij}}}+\frac{c_5+\omega_{ij}c_6}{T_{r_{ij}}^2}+\frac{c_7+\omega_{ij}c_8}{T_{r_{ij}}^6}\right] \tag{16}$$

where the critical properties T_{cij}, V_{cij} and ω_{ij} are defined as:

$$T_{c_{ij}}=\sqrt{T_{c_i}T_{c_j}} \tag{17}$$

$$\hat{V}_{c_{ij}}=\left(\frac{\hat{V}_{c_i}^{1/3}+\hat{V}_{c_j}^{1/3}}{2}\right)^3 \tag{18}$$

$$\omega_{ij}=\frac{\omega_i+\omega_j}{2} \tag{19}$$

In Eq. (16),

c_1=0.442259	c_2=0.725650
c_3=−0.980970	c_4=0.218714
c_5=−0.611142	c_6=−1.24976
c_7=−0.11515624	c_8=−0.189187

4. Third Virial Coefficients

The generalised empirical correlation of Orbey and Vera [1983] is used to estimate the third virial coefficients:

$$\frac{CP_c^2}{(RT_c)^2}=g_1+\omega g_2 \tag{20}$$

where, C is the third virial coefficient, P_c is the critical pressure, T_c is the critical temperature, R is the Universal gas constant, ω

is the acentric factor, and g_1 and g_2 are both functions of the reduced temperature:

$$g_1 = 0.01407 + \frac{0.02432}{T_r^{2.8}} - \frac{0.00313}{T_r^{10.5}} \tag{21}$$

$$g_2 = -0.02676 + \frac{0.01770}{T_r^{2.8}} + \frac{0.040}{T_r^{3.0}} - \frac{0.003}{T_r^{6.0}} - \frac{0.00228}{T_r^{10.5}} \tag{22}$$

5. Third Virial Cross Coefficients

The two third virial cross coefficients for the each of the systems, B_{iij} and B_{ijj}, are estimated using the empirical correlation of Orbey and Vera [1983]. Brugge et al. [1989] found this correlation to be good for estimating for cross coefficients for three different systems. The correlation is

$$C_{ijk} = (C_{ij} C_{ik} C_{jk})^{1/3} \tag{23}$$

where,

$$C_{ij} = \left(\frac{RT_{c_{ij}}}{P_{c_{ij}}}\right)^2 (g_1 + \omega_{ij} g_2) \tag{24}$$

and g_1 and g_2 are both functions of T_{rij} defined in Eqs. (21) and (22). The cross critical temperature and cross acentric factor are defined as in Eqs. (17) and (19), respectively. The cross critical pressure is defined as

$$P_{c_{ij}} = 4(Z_{c_i} + Z_{c_j}) T_{c_{ij}} \left[\left(\frac{Z_{c_i} Z_{c_j}}{P_{c_i}}\right)^{1/3} + \left(\frac{Z_{c_i} Z_{c_j}}{P_{c_j}}\right)^{1/3} \right]^{-3} \tag{25}$$

6. Vapour Pressure

The vapour pressure correlation of ESDU [1984] is used for the three alcohols:

$$\ln P_v = \ln P_c + \frac{1}{T_r} [c_1(1-T_r) + c_2(1-T_r)^{3/2} + c_3(1-T_r)^3 + c_4(1-T_r)^6] \tag{26}$$

The coefficient values for the three alcohols of interest are presented in Table 3.

7. Isothermal Compressibility

Isothermal compressibility may be related to temperature by a correlation of the form:

$$\kappa = \left[\frac{c_1 + c_2 t + c_3 t^2 + c_4 t^3}{1 + c_5 t}\right] \times 10^{-10} \tag{27}$$

where κ is the isothermal compressibility expressed in 1/Pa, and t is the temperature expressed in °C. Table 4 presents the values for the coefficients regressed for the materials of interest from the data presented by McGowan [1980].

Table 3. Vapour pressure coefficients for Eq. (26)

Component	c_1	c_2	c_3	c_4
Methanol	−8.48173	0.57085	−2.63162	−0.20051
Ethanol	−8.33383	−0.21797	−4.27288	2.31481
n-Propanol	−8.11332	0.14612	−7.60583	7.00215

Table 4. Isothermal compressibility coefficients for Eq. (27)

Component	c_1	c_2	c_3	c_4	c_5
Methanol	10.699	1.441	0.0114	0	0.131
Ethanol	9.790	54.40	0.2601	0.00310	5.493
n-Propanol	8.43	0	0	0	0

Table 5. Molar volumes of liquid coefficients for Eq. (28)

Component	c_1	c_2	c_3	c_4
Methanol	2.0168	−0.6763	−0.6505	0.6505
Ethanol	1.5676	1.0330	−2.8375	1.5379
n-Propanol	1.9808	−1.3267	1.3620	−0.8172

8. Molar Volume of Condensed Phase

The molar volumes of the liquid alcohols may be related to temperature by equations of the form:

$$\ln \hat{V}_{V_c} = \ln \hat{V}_c + \sum_{i=1}^{4} c_i (1-T_r)^{1/3} \tag{28}$$

where, $\hat{V}_{V_c}$ is the molar volume of the condensed phase expressed in cm^3/mol, and $\hat{V}_c$ is the critical volume. The values for the coefficients presented in Table 5 are taken from ESDU [1989].

9. Henry's Law Constants

The solubility of the nitrogen in the liquid alcohols is considered by making use of Henry's law constants, k_H. These constants are related to temperature by the equation,

$$k_H = \frac{1}{\exp(c_1 + c_2/T)} \tag{29}$$

Here k_H is expressed in atm, and T in Kelvin. For the nitrogen-alcohol systems of interest the coefficients are presented in Table 6. Data is taken from Battino [1982].

10. Heat Capacity Data

The ideal gas heat capacity for each component is assumed to be a cubic function of absolute temperature:

$$C_P = c_1 + c_2 T + c_3 T^2 + c_4 T^3 \tag{30}$$

Reid et al. [1977] tabulate the ideal gas heat capacity coefficients for a range of gases. These coefficients are presented in Table 7, after they have been converted so that C_P is expressed in J/g-mol K and T is expressed in Kelvin.

11. Latent Heat of Vaporization

The latent heat of vaporization for the alcohols may be related to temperature by [ESDU, 1973]:

$$\lambda = \sum_{i=1}^{6} c_i (1-T_r)^{i/3} \tag{31}$$

Here λ is the latent heat of vaporization expressed in kJ/kg. Values for the six coefficients for each of the alcohols are pre-

Table 6. Henry's law coefficients for Eq. (29) for alcohol vapours in nitrogen

Component	c_1	c_2
Methanol	−8.1708	−6.9897
Ethanol	−7.9531	−4.4380
n-Propanol	−7.9060	25.743

Table 7. Ideal gas heat capacity coefficients for Eq. (30)

Component	c_1	$c_2 \times 10^2$	$c_3 \times 10^5$	$c_4 \times 10^9$
Methanol	21.15	7.092	2.587	−28.52
Ethanol	9.01	21.41	−8.390	1.272
n-Propanol	2.47	33.25	−18.55	42.96

Table 8. Latent heat of vaporization coefficients for Eq. (31)

Component	c_1	c_2	c_3	c_4	c_5	c_6
Methanol	2462.3	−4105.5	3120.8	4865.4	−2893.6	−2917.1
Ethanol	1014.2	863.26	643.60	−780.73	−2051.7	1370.6
n-Propanol	2222.5	−8368.4	14567	−2870.3	−9655.7	4966.0

Table 9. Condensed phase enthalpy coefficients for Eq. (32)

Component	c_1	c_2	c_3	c_4
Methanol	−84.89	0.1550	−0.7130	−0.4725
Ethanol	−127.8	0.1650	−0.7285	−0.4547
n-Propanol	−163.4	0.1705	−0.7380	−0.4460

sented in Table 8.

12. Enthalpy of the Condensed Phase

For the liquid alcohols ESDU [1979] recommend the use of a correlation of the form:

$$\hat{h}_f = -c_1 T_c \left\{ \left[\left(1 - \frac{T}{T_c}\right) - \left(1 - \frac{T}{T_{datum}}\right) \right] + 3c_2 \left[\left(1 - \frac{T}{T_c}\right)^{1/3} - \left(1 - \frac{T}{T_{datum}}\right)^{1/3} \right] \right.$$
$$+ \frac{3}{2}c_3 \left[\left(1 - \frac{T}{T_c}\right)^{2/3} - \left(1 - \frac{T}{T_{datum}}\right)^{2/3} \right]$$
$$\left. + \frac{3}{4}c_4 \left[\left(1 - \frac{T}{T_c}\right)^{4/3} - \left(1 - \frac{T}{T_{datum}}\right)^{4/3} \right] \right\} \quad (32)$$

where, $\hat{h}_f$ is expressed in kJ/kg, and T, T_c and T_{datum} are expressed in Kelvin. The enthalpy datum condition is taken as a liquid at T_{datum}. Values for the four coefficients are presented in Table 9.

NOMENCLATURE

B : second virial coefficient
c : correlation coefficient
C : third virial coefficient
C_P : ideal gas heat capacity
f : enhancement factor
g_1, g_2 : functions defined in Eqs. (21) and (22)
$\hat{h}$: real gas specific enthalpy
$\hat{h}_{dev}$: enthalpy deviation
$\hat{h}_f$: condensed phase enthalpy
$\hat{h}_o'$: enthalpy correction
k_H : henry's law constant
MW : molecular weight
P_c : critical pressure
P_V : vapour pressure
P_T : total pressure
R : universal gas constant
T : absolute temperature
T_{ad} : adiabatic saturation temperature
T_c : critical temperature
T_{datum} : enthalpy datum temperature
T_r : reduced temperature
V_c : critical volume
V_{Vc} : liquid molar volume
x : mole fraction
Z_c : critical compressibility factor

Greek Letters

ϕ : relative humidity
κ : isothermal compressibility
λ : latent heat of vaporization
ω : acentric factor

Subscripts

G : non-condensing gas component
m : mixture
S : saturation condition
V : condensing vapour component

REFERENCES

ASHRAE, "ASHRAE Handbook-Fundamentals SI Edition," 1989.
Battino, R., "Solubility Data Series-Volume 10-Nitrogen and Air," Pergamon Press, Oxford (1982).
Brugge, H. B., Yurttas, L., Holste, J. C. and Hall, K. R., "Comparison of Methods for Calculating Third Virial Coefficients: Application to Binary Mixtures of CO_2 with N_2, CH_4 and C_2H_6," *Fluid Phase Equilibria*, **51**, 187 (1989).
ESDU, "Heat Capacity and Enthalpy of Liquids: II : Halogenated Methanes," Engineering Sciences Data Unit International, London, Item Number 79028 (1979).
ESDU, "Heat Capacity and Enthalpy of Liquids: Aliphatic Ketones," Engineering Sciences Data Unit International, London, Item Number 81030 (1981).
ESDU, "Orthobaric Densities and Molar Volumes of Liquids: Alcohol," Engineering Sciences Data Unit International, London, Item Number 89037 (1989).
ESDU, "Vapour Pressure and Critical Points of Liquids: Part 1 A : C_1 to C_7 Alkanes," Engineering Sciences Data Unit International, London, Item Number 84022 (1984).
Hyland, R. W. and Wexler, A., "Formulations for the Thermodynamic Properties of Dry Air from 173.15 K to 473.15 K, and of Saturated Moist Air from 173.15 K to 372.15 K at Pressure to 5 MPa," *ASHRAE Transactions*, **89**(2A), 520 (1983).
Kehianian, H. V., "Virial Coefficients of Selected Gases," in "CRC Handbook of Chemistry and Physics," 77th edn (ed D. R. Lide), CRC Press, Boca Racon, Florida, 6-27-6-46 (1996).
McGowan, J. C., "Isothermal Compressibility of Liquids," in "CRC Handbook of Chemistry and Physics," 60th edn (eds R. C. Weast and M. J. Astle), CRC Press, Boca Raton, Florida, F-16-F-20 (1980).
Pitzer, K. S., "Second Virial Coefficients for Mixed Gases of Low Polarity," *Fluid Phase Equilibria*, **59**, 109 (1990).
Orbey, H. and Vera, J. H., "Correlation for the Third Virial Coefficient using T_c, P_c and ω as Parameters," *American Institute of Chemical Engineers Journal*, **29**(1), 107 (1983).
Reid, R. C., Prausnitz, J. M. and Sherwood, T. K., "The Properties

of Gases and Liquids," 3rd edn, McGraw-Hill Book Company, New York (1977).

Shallcross, D. C. and Low, S. L., "Construction of Psychrometric Charts for Systems Other Than Water Vapour in Air," *Chem. Eng. Research Design*, **72**, 763 (1994).

Shallcross, D. C., "Handbook of Psychrometric Charts," Chapman and Hall, London (1997).

Shallcross, D. C., "Psychrometric Charts for Hydrocarbon Vapours in Nitrogen," *Calphad*, **20**(3), 283 (1996).