



Research paper

## Psychrometric charts for water vapour in natural gas

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### ABSTRACT

Psychrometric charts present in a graphical form physical property data for gas systems involving one or more non-condensing gas components and a single condensing vapour component. Originally limited to studying the humid air system of water vapour in dry air, the theory behind preparing psychrometric charts for water vapour in natural gas is presented. To illustrate the technique two charts are prepared for a system in which the natural gas is 80.0 mol% methane, 15.0 mol% ethane and 5.0 mol% propane. One chart is prepared for the temperature range of 0 to 60 °C at a system pressure of 101.3 kPa and the other chart for the range of 40 to 110 °C at a system pressure of 400.0 kPa. The charts are based upon semi-theoretical equations and make use of published physical property data and correlations. The behaviour of the gas mixture is characterized by the virial equation of state truncated at the third term. 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. Using the theory presented psychrometric charts for any temperature range, system pressure and natural gas composition may be prepared.

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### 1. Introduction

An understanding of the conditions under which water vapour may condense from natural gas is important in the design and operation of any system involving the use, transportation or storage of natural gas. Even in this age of computer-aided design and physical property databases, engineers still find it useful to have physical property data presented graphically. Using a simple straight line or curve overlaid onto a chart of physical property data variations in the properties may be observed as a function of some changing parameter.

Psychrometric charts present in a graphical form physical property data for gas systems involving one or more non-condensing gas components and a single condensing vapour component. Originally limited to studying the humid air system of water vapour in dry air, psychrometric charts have now been extended to other systems (Shallcross and Low, 1994; Shallcross 2005).

In this paper the application of psychrometric charts is extended to consider systems involving water vapour in natural gas. The wide range of natural gas compositions is represented in this study by considering a three-component natural gas mixture of 80.0 mol% CH<sub>4</sub>, 15.0 mol% C<sub>2</sub>H<sub>6</sub> and 5.0 mol% C<sub>3</sub>H<sub>8</sub>. However, nothing in the development or application of the equations presented here limits the system to just three non-condensing components. Two psychrometric charts covering differing temperature ranges and differing pressures are prepared to illustrate the preparation of such charts.

### 2. Modelling system behaviour

In modeling the system properties the gas phase is not assumed to behave ideally. The effects of the dissolved gases and the pressure on the properties of the condensed phase (i.e., the water) are accounted for as is the effect of intermolecular forces on the properties of the moisture. The virial equation of state truncated at the third term is used to characterize the non-ideal behaviour. This method is chosen from the many equations of state in the literature as virial coefficient data is readily available for a range of systems and components. The virial equation of state truncated at the third term is:

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

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 humid natural gas, respectively.

In the development of the model equations which follow we shall assume that the natural gas may be represented as a single component, G. The vapour component (i.e., the water vapour) that readily condenses will be denoted as V.

If  $x_G$  is the mole fraction of the non-condensing natural gas, and  $x_V$  is the mole fraction of the water vapour then for a binary system:

$$B_m = x_G^2 B_{GG} + 2 x_G x_V B_{GV} + x_V^2 B_{VV} \quad (2)$$

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

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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.

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:

$$x_{Vs} = \frac{P_V}{P_T} \quad (4)$$

and

$$x_{Gs} = \frac{P_T - P_V}{P_T} \quad (5)$$

where,  $x_{Vs}$  and  $x_{Gs}$  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 an enhancement factor is used to account for the non-idealities in the system. Eq. (4) becomes,

$$x_{Vs} = \frac{f P_V}{P_T} \quad (6)$$

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

$$x_{Gs} = \frac{P_T - f P_V}{P_T} \quad (7)$$

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. The enhancement factor may be written in terms of the virial coefficients and the other properties of the system (Hyland and Wexler, 1983):

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

Here  $\kappa$  is the isothermal compressibility of the condensing component (i.e. the water),  $\hat{V}_{Vc}$  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,  $P_T$ , Eqs. (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 using Eq. (7) and this value is used in Eq. (8) to calculate an estimate for the enhancement factor,  $f$ . The value for  $x_{Gs}$  is then re-calculated. 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:

$$H_s = \frac{x_{Vs}}{x_{Gs}} \frac{MW_V}{MW_G} \quad (9)$$

where  $MW_i$  is the molecular weight of component  $i$ .

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 psychrometric chart is drawn by plotting the absolute humidity at saturation,  $H_s$ , as a function of temperature for a specified total pressure.

The relative humidity,  $\phi$ , 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,

$$\phi = \frac{x_V}{x_{Vs}} \quad (10)$$

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. It may be shown that (Shallcross and Low, 1994):

$$H = \frac{H_s \phi (1 - f P_V / P_T)}{1 - \phi f P_V / P_T} \quad (11)$$

To construct the constant relative humidity curves, the system pressure,  $P_T$ , is first specified. Then for a given value of  $\phi$ , 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,  $v$ , is defined as the volume of the mixture per unit mass of the dry gas:

$$v = \frac{\hat{V}}{x_G MW_G} \quad (12)$$

Applying this definition and using Eq. (1) 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  $V$ , in this case water. As the moist gas passes the thermometer some of the water 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. As 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, it is not possible to predict the wet bulb temperatures with precision. Consequently we choose to plot instead curves of constant adiabatic saturation temperature.

For the conventional air–water system the adiabatic saturation temperature,  $T_{ad}$ , is defined 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 (ASHRAE, 1989). 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

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