Measurement of humidity

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Abstract

This article describes the physical chemistry of evaporation with particular relation to water. The concept of humidity is defined, and factors that influence humidity are discussed in a practical context. The clinical importance of measurement and control of humidity is illustrated. Commonly used methods of measuring humidity are described and their underlying physical principles are explained.

Keywords Dew point; humidity; hygrometer; measurement; saturated vapour pressure; vapour pressure

Royal College of Anaesthetists CPD Matrix: 1A03, 2A04

Learning objectives

After reading this article, you should be able to:
- define the terms: vapour pressure, absolute humidity, relative humidity and dew point
- discuss the clinical relevance of measuring and controlling humidity
- explain the principles of devices used to measure humidity

Introduction

Humidity is the amount of water vapour present in a sample of gas, expressed as weight or volume of water vapour per unit weight or volume of gas. A **hygrometer** is an instrument which measures humidity.

A **vapour** is the gaseous form of a substance at a temperature below its **critical temperature**: the temperature above which it is not possible to liquefy the substance regardless of the pressure applied. Temperature is a direct measure of mean molecular kinetic energy; however, individual molecules have a wide range of different energy states. The more energetic molecules escape from the surface of the liquid phase and enter the space above where they exert a pressure (**vapour pressure**). When dynamic equilibrium is reached, the rate at which molecules leave the liquid into the space above equals the rate at which they re-enter the liquid. At this point, the space above the liquid is saturated with vapour and the vapour exerts a **saturated vapour pressure** (SVP). Vapour pressure and SVP are therefore primarily dependent on the nature and temperature of the liquid. A similar process occurs in crystalline solids, but to lesser degree (e.g. ice has an associated vapour pressure). Atmospheric pressure is the sum of the partial pressures of its component gases and vapours (**Dalton's law**). **Water vapour pressure** (P_{H2O}; kPa) is the partial pressure of water vapour in a gas which is in equilibrium with solid or liquid water.

As water is heated, the total and mean energy state of the molecules increases, evaporation occurs more readily and P_{H2O} will increase. If equilibrium conditions are re-established, SVP will also increase. At a typical room temperature of 22°C (295 K), the SVP of water is 2.65 kPa. This increases to 6.28 kPa at body temperature of 37°C (310 K). Thus, if room air at a temperature of 22°C is fully saturated with water vapour, it will contain 2.65/101.3 = 2.62% water vapour.

The approximately exponential relationship between saturated vapour pressure and temperature is described by the **Antoine equation** and the **Clausius–Clapeyron equation**.[a] As temperature increases, P_{H2O} increases. When the temperature has increased to the point where vapour pressure is equal to the ambient pressure, the water reaches its **boiling point**. If ambient pressure is reduced, the boiling point decreases.

If more energetic molecules forming the vapour are removed (e.g. by passing a flow of gas over the liquid), then the total and mean energy state is reduced and the water cools. Excess water is deposited as mist, dew, condensation (or frost if ambient temperature <0°C).

Humidity

For a given volume of gas at a given temperature and pressure, we can define the following terms.

Absolute humidity (H_A; g/m^3, or mg/litre): the mass of water vapour present per unit volume of gas. If the gas is fully saturated with water vapour, this is referred to as the **absolute humidity at saturation**. Gases expand when warmed, therefore H_A will decrease slightly with increasing temperature: e.g. if 1 litre of air at 22°C containing 10 mg water is warmed to 37°C, the volume will increase to 1.05 litres, and H_A will decrease to 9.5 mg/litre.

Specific humidity (H_S; mg/kg): the mass of water vapour per unit mass of gas. The mass of air, and therefore H_S, remains the same as temperature and pressure vary.

Mixing ratio: the ratio of the mass of water vapour in the gas sample to the mass of the dry gas.

Relative humidity (H_R; %): the amount of water vapour present expressed as a percentage of the maximum possible amount which could be present (i.e. H_A at saturation) at that temperature and pressure.

[a] $ln(\frac{P_1}{P_2}) = (\frac{\Delta H_v}{R})(\frac{1}{T_2} - \frac{1}{T_1})$, where: $P_{1,2}$ (kPa) are vapour pressures of water at temperatures $T_{1,2}$ (K); ΔH_v (J) is the enthalpy of vaporization; R is the universal gas constant = 8.314 J/K/mol.

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$$H_R\ (\%) = 100 \times P_{H2O}/SVP_{H2O}$$

For example, for room air at 22°C and H_A 10 g/m^3, H_R = 10/19.51 = 51%, where 19.51 g/m^3, is H_A at saturation at 22°C.

Dew point (T_D; K): as the gas is cooled, this is the temperature at which condensation of water commences. At the dew point, air is saturated with water, i.e. $P_{H2O} = SVP_{H2O}$; H_R = 100%.

Ambient air at room temperature is not usually saturated with water vapour (typically: 22°C; SVP = 2.65 kPa; $H_R \approx$ 60%; H_A = 10 mg/litre) (point A, Figure 1). If the temperature decreases, the mass of water vapour will remain the same, but H_A at saturation decreases and H_R will increase. At a temperature of about 11°C (284 K), the air becomes fully saturated with water vapour (the moisture content is equal to H_A at saturation) and the H_R is thus 100% (point B, Figure 1). If the gas cools any further, T_D will be reached and condensation will occur. Hence cooling (or compressing) moist air will cause some of the water content to condense and dry the sample: some dehumidifiers utilize this principle.

Conversely, if the original room air is warmed, H_R will decrease as H_A at saturation increases. Therefore, more water vapour needs to be added to a gas at a higher temperature to maintain a particular level of H_R. For example, typical room air (H_R 50% at 22°C) will have H_R of only 9.5/44 = 22% at 37°C (point C, Figure 1). The water-holding capacity of the atmosphere increases by about 7% per 1°C rise in temperature: hence tumble driers use warm air to remove water from clothing.

Air in the lungs is at body temperature and fully saturated with water vapour ('body temperature and pressure, saturated', BTPS: 310 K, 37°C; SVP = 6.3 kPa; H_R = 100%; H_A = 44 mg/litre). The **humidity deficit** is the difference between the moisture content of air at BTPS and the moisture content of inspired air. If a patient inhales typical room air, the humidity deficit is 9.5−44 = −34.5 g/m^3. Therefore, 34.5 g/m^3 of water vapour must be added by the patient's upper airways to humidify the inspired air (indicated by the arrows, Figure 1). Anaesthetic gases are desiccated to prevent corrosion to pipelines and cylinders and have negligible water content ($H_A \approx$ 0 g/m^3). Therefore when anaesthetic gases are inhaled, the humidity deficit increases to −44 g/m^3.

As the patient exhales, the gas cools slightly, so that at the mouth, the temperature is about 34°C (307 K). At this temperature, the moisture content at saturation is about 38 g/m^3. This is the maximum amount of moisture that can be returned by a heat and moisture exchanger (HME), a passive device that is intended to return a portion of the patient's exhaled moisture in the next inspiration. If the efficiency of the HME is 80%, then the moisture content of the inspired air is 30 g/m^3. In this case, the airways would have to add a further 14 g/m^3 of water vapour to increase the absolute humidity of the air in the lungs to 44 g/m^3.

As the exhaled air cools to room temperature, the SVP falls to 2.65 kPa; and the excess water will visibly condense on the surroundings (e.g. expiratory limb of the breathing system).

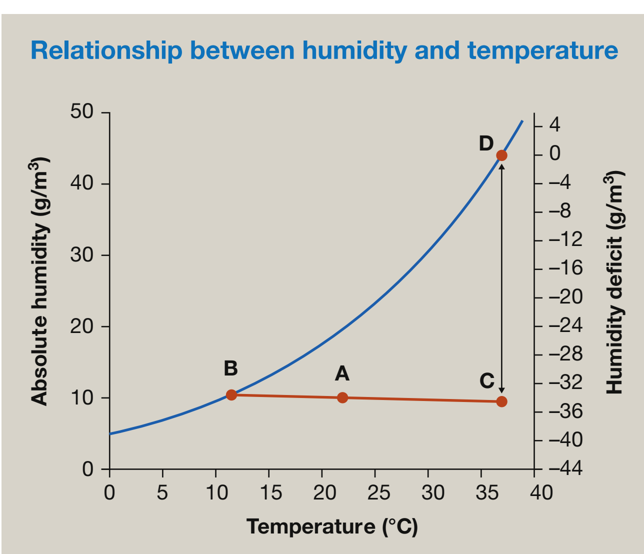

Figure 1

Clinical relevance

Measurement and control of humidity is important because:

- The upper respiratory tract filters, warms and humidifies inhaled gases. If this is bypassed by a tracheal or tracheostomy tube, inspired gases will be inadequately humidified, resulting in increased insensible fluid loss, depression of pulmonary cilial activity, thickening of secretions and atelectasis. Therefore humidifiers are incorporated into intensive care and anaesthetic breathing systems. These may be active (nebulizers) or passive (HMEs, circle system with soda lime).
- Low ambient humidity prevents conduction of static electricity to earth. Accumulation of static charge presents a potential microshock and fire hazard.
- High ambient humidity predisposes to microbial growth and prevents heat loss through perspiration which may lead to heat-related illness. Low ambient humidity predisposes to evaporative loss of heat and fluids (especially in small children and patients with burn injuries). Therefore operating theatres are usually maintained at temperatures of 20−24.5°C and H_R 40−60%.
- If a gas cylinder is inadequately dried (e.g. following hydraulic testing), so that it contains some residual water, the humidity of the delivered gas will increase as the cylinder is discharged and pressure falls.

Measurement of humidity

Hair hygrometer: a strip of nylon or cellulose (traditionally a human hair was used) absorbs water and increases in length as humidity increases. The strip is connected via a mechanical linkage to a pointer; or via an electronic strain gauge and digital readout; to display H_R (Figure 2a). Response time, range (H_R 5−85%) and accuracy (±5%) are poor; but the simple low-cost design is adequate for monitoring environmental humidity in operating theatres.

Wet and dry bulb hygrometer: two liquid-in-glass thermometers are mounted side-by-side. One thermometer is exposed to the atmosphere. The bulb of the other thermometer is enclosed in a muslin wick which is kept constantly wet by a water reservoir

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