HUMID AIR

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WHAT IT IS

All natural air is humid; dry air must be artificially obtained. Humid air is the most important gaseous mixture in science and engineering: from breathing to meteorology and air conditioning. The atmosphere is a heterogeneous mixture of gases (the air, properly) and liquid and solid particles in suspension (clouds, dust, microorganisms...).

Humid air can be modelled as a binary gas mixture of dry air and water vapour because none of the components of dry air is highly soluble in liquid water, and dry-air composition can be considered invariable. The two-phase binary mixture of water and air is not an ideal mixture in both phases, but for the gaseous phase the ideal mixture model is very appropriate, and Raoult's law for the two-phase equilibrium of water still valid. As for the liquid phase, Henry law can be applied, but, if one takes into account that air scarcely dissolves in water (at 100 kPa and 288 K $x_{LN2}=10\cdot10^{-6}$ and $x_{LO2}=10\cdot10^{-6}$, increasing with pressure and decreasing with temperature), one may neglect that and consider that equilibrium is with pure water. Notice, by the way, that oxygen dissolves more than nitrogen in water.

When does air need to be considered humid? In many engineering problems, air does not change composition or the changes are irrelevant; in those cases there is no need for humid air formulation and air can be treated as a pure substance (from aircraft lifting to most heat transfer problems). But in some cases the change in composition of the air may be crucial, either because condensation occurs or because

air entrains water from some source, as from vital meteorological processes, to artificial air conditioning and evaporative cooling.

WHAT IS FOR: APPLICATIONS

The study of humid air is known as hygrometry (Gr. υγροζ, humid), or psychrometry (Gr. ψυχρόν, cold). No distinction will be made here between humid air in contact with a condensed phase of water through a single interface (air over water), and when the condensed phase is dispersed in the air (mists and fogs).

Notice that the theory of humid air may be applied (changing the data accordingly) to any other binary mixture of a condensing substance dissolved in a non-condensing gas, as sulphuric acid in dry air (e.g. to study acid rain), water in combustion-exhaust gases, sulphuric acid in combustion-exhaust gases, water in hydrogen (to keep moisten the electrolyte in fuel cell applications), etc.

Notice also that, with the simplification of a non-dissolving dry gas, the saturating water-vapour molar-fraction only depends on temperature and pressure, and not on the dry-gas composition (e.g. in equilibrium with pure liquid water at 300 K and 100 kPa, the molar fraction of water-vapour would be 3.6% either in air, hydrogen, carbon dioxide, or any mixture of dry non-condensable gases).

HUMIDITY SPECIFICATION

The thermodynamic state of a sample of humid air, as a binary homogeneous mixture (of dry air and water vapour, in gas phase), requires three intensive variables to be fully specified: pressure, temperature and humidity, the latter being determined by several different variables, all of them related.

We have said in Chapter 7 that molar fractions are the best variables to specify mixture composition (recall; because, in the limit, mixture properties only depend on amount of substance involved, e.g. $pV=\Sigma n_i RT$, $S=-k\Sigma x_i \ln x_i$). Thence, adopting subindices 'a' for 'dry air' and 'v' for 'water vapour', besides the water-vapour fraction, x_v, defined as always by:

$$\text{vapour molar fraction in gas phase: } x_v \equiv \frac{n_v}{n_a + n_v} \tag{8.1}$$

and Raoult's law for water (i.e. the equality of the chemical potential of water in the liquid-gas equilibrium:

$$\text{vapour molar fraction in gas phase saturated with pure water: } x_{v_{sat}} = \frac{p^*(T)}{p} \tag{8.2}$$

it is customary to introduce new thermodynamic variables in the study of air-water mixtures: relative humidity, absolute humidity, dew temperature and wet temperature. Equation (8.2) is the water-vapour molar fraction at saturation, given by Raoult's law (7.23) with the molar fraction of H_2O in the liquid phase set equal to 1 (i.e. pure or near pure water, but not valid for concentrated aqueous solutions). Notice that $p^*(T)$ is the pressure at liquid-vapour equilibrium (LVE) at a flat interphase, also named 'saturation' vapour pressure (in Meteorology, vapour pressure usually refers to partial vapour pressure, $x_v p^*(T)$).

Relative humidity and humidity ratio

The maximum amount of water-vapour that dry-air can dissolve when in contact with liquid water is $x_{v,sat}$ given by (8.2), which for air at room conditions of 20 °C and 100 kPa is just $x_{v,sat}=p^*(T)/p=2.3/100=0.023$, a small percentage; what really matters is not this small amount, but the great effect of condensation and evaporation processes, so that, more important than the actual composition measured by x_v, is the ratio $x_v/x_{v,sat}$, which marks the proximity of saturation in a more natural way, and which is named relative humidity:

$$\text{relative humidity (RH): } \phi \equiv \frac{x_v}{x_{v_{sat}}} \tag{8.3}$$

But relative humidity does not give an indication of how much vapour there actually is (unless complemented by p-T-values), as specified by x_v, although, as said before, another new variable is preferred, the humidity ratio or absolute humidity, w, defined by:

$$\text{humidity ratio (moisture content, or absolute humidity): } w \equiv \frac{m_v}{m_a} \tag{8.4}$$

the reason for not using the total mass but the mass of dry air is that air and water are very dissimilar substances, and for the range of temperatures and pressures envisaged, one of the components (dry air) may be thought as permanently in the gas phase, while water vapour can be easily changed, and thus it is advantageous to refer concentrations, enthalpies, and other thermodynamic functions, to the conservative mass of dry air.

Notice that no saturation is possible for temperatures above the boiling point of pure water at that pressure (or at a pressure lower than the pure-vapour pressure at that temperature), and thus relative humidity is ill-defined in these cases (humidity ratio is still well-defined). The variance for the gaseous humid-air system is $V=2+C-F=2+2-1=3$, so that, if T and p are fixed, there is only one parameter left to specify the composition (ϕ is the most used), and the relation with the others is:

$$x_v = \frac{1}{\dfrac{M_{va}}{w}+1} = \frac{\phi\, p^*(T)}{p} \tag{8.5}$$

$$\phi = \frac{1}{\dfrac{p^*(T)}{p}\left(\dfrac{M_{va}}{w}+1\right)} = \frac{x_v}{\dfrac{p^*(T)}{p}} \tag{8.6}$$

$$w = \frac{M_{va}}{\dfrac{p}{\phi\, p^*(T)}-1} = \frac{M_{va}}{\dfrac{1}{x_v}-1} \tag{8.7}$$

where $M_{va}=M_v/M_a=0.018/0.029=0.622$. Humidity can be measured with a variety of instruments, from the modern electrical capacitance transducer, to the traditional sling psychrometer or the ancient hair indicator.

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Humid air density can be approximated by dry air density in most applications; if not, the ideal gas mixture models yields $\rho=p(x_aM_a+x_vM_v)/(R_uT)=\rho_a(x_a+x_vM_{va})=\rho_a[1-(1-M_{va})\phi p^*/p]$, i.e. the relative error when approximating by dry air density is $(1-0.622)\phi p^*(T)/p$, typically around 1%.

Exercise 1. Water condensation in air compression

Dew point and frost point

For a given humid-air condition, (T,p,ϕ), two processes are defined that have special names. The dew point is reached when cooling the humid air until saturation, at constant pressure and composition, what yields:

$$p^*(T_{dew}) = \phi\, p^*(T) \quad \Rightarrow \quad \frac{T_{dew}}{T_u} = \frac{1}{\dfrac{1}{\dfrac{T}{T_u}+C} - \dfrac{\ln\phi}{B}} - C \tag{8.8}$$

where Antoine equation for vapour pressure is substituted ($T_u=1$ K is used to non-dimensionalise, and Antoine's coefficients A, B and C can be found in Tables). in Meteorology, the vapour pressure over liquid water is used even when there is ice at <0 ºC, although vapour pressure over ice is slightly lower. It was Regnault around 1830 the first to use the measurement of dew-point temperature (cooling with vaporising ether a mirror until it glazed), as a measure of relative humidity $\phi=p^*(T_{dew})/p^*(T)$; he was the first also to measure vapour pressure over ice, in 1847.

Where the condensate is ice, i.e., below the freezing temperature, the corresponding temperature is known as the frost point instead of the dew point. Hoarfrost is the white deposit of ice particles formed on leaves and other objects out of doors at night. Frosting is more embarrassing to get rid of than condensation as dew, because the ice-sheet formed sticks on the solid surface, whereas the liquid water condensed drips naturally by gravity.

We have assumed equilibrium conditions for humid-air cooling, but metastable states can be reached when nucleation sites are scarce; with normal atmospheric air it is uncommon to surpass 1..2% supersaturation (i.e. $\phi>1.02$), but, under controlled conditions, higher values are obtained. Much higher supersaturation values can be found in the phase transition from microscopic water droplets to ice crystals on clouds, which may be retarded from 0 ºC to −40 ºC in absence of ice nuclei.

Adiabatic saturation temperature and wet bulb temperature

The adiabatic saturation point is reached when adding liquid water to humid air until saturation at steady state and without letting it exchange heat (neither work) with the environment (Fig. 8.1).

To solve for the adiabatic saturation temperature, the mass and energy balances are imposed, so we have to choose reference values for energies for each component. The usual choice in humid-air formulation is to assign zero enthalpy for liquid water at 0 ºC (practically the same reference as in the Mollier water-

diagram: zero internal energy for liquid water at the triple point, 0.01 °C), and zero enthalpy for dry air at 0 °C. Besides, as justified above when defining the humidity ratio, it is customary to work with enthalpies per unit mass of dry air, instead of per unit mass of mixture, that is, with the perfect gas model (PGM):

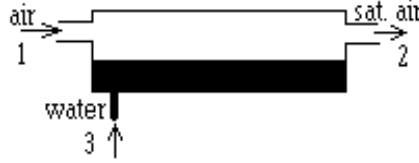$$h \equiv \frac{H}{m_a} \overset{\text{PGM}}{=} c_{pa}(T - T_0) + w\left[h_{LV0} + c_{pv}(T - T_0)\right] \tag{8.9}$$

Fig. 8.1. The adiabatic saturation process.

Thence, the species and energy balance for the adiabatic saturation process are:

mass balance for dry air: $\dot{m}_{a1} = \dot{m}_{a2}$ (8.10)

mass balance for water: $\dot{m}_{a1}w_1 + \dot{m}_3 = \dot{m}_{a2}w_2$ (8.11)

energy balance: $\dot{m}_{a1}h_1 + \dot{m}_3h_3 = \dot{m}_{a2}h_2$ (8.12)

the last one obtained from (5.3) for steady state, with Q=0, W=0 and (8.9). The fact that the enthalpy of the supply water is very small (small flow rate, and liquid state), means that the energy balance may be approximated to h_1=h_2, i.e. an isenthalpic process for the humid air, that with the perfect gas model, and neglecting the sensible enthalpy of water vapour with respect to its latent enthalpy, yields:

$$h_1 = h_2 \quad \rightarrow \quad c_{pa}(T_1 - T_0) + w_1 h_{LV0} = c_{pa}(T_2 - T_0) + w_2 h_{LV0}$$

$$\rightarrow \quad c_{pa}(T_1 - T_0) + \frac{M_{va}}{\dfrac{p}{\phi_1 p^*(T_1)} - 1} h_{LV0} = c_{pa}(T_2 - T_0) + \frac{M_{va}}{\dfrac{p}{p^*(T_2)} - 1} h_{LV0} \tag{8.13}$$

allowing the computation of the adiabatic saturation temperature, T_2, corresponding to some humid air condition (T_1, p_1, ϕ_1), by iterative calculation, since the vapour pressure is an exponential function (as in the integrated Clapeyron's equation or the more commonly used Antoine's equation).

The wet bulb temperature, T_{wet}, is the temperature a small wet-object would reach, by evaporative cooling, when exposed to an air flow. When the combined heat and mass transfer problem is solved, it happens that the value of T_{wet} is approximately the adiabatic saturation temperature. Because T_{wet} is easy to measure (just blowing over a thermometer with its bulb surrounded by a small mesh soaked in water), it was customarily used to measure humidity by rotating a set-up with two equal mercury-thermometers, one of them with the bulb wrapped with a wick soaked in water (sling psychrometer). A good approximation to find relative humidity, ϕ, from dry and wet temperatures, T and T_{wet}, is obtained by neglecting the '−1' in (8.13):

$$\phi = \frac{p^*(T_{\text{wet}})}{p^*(T)} - \frac{c_{pa}(T - T_{\text{wet}})}{M_{va} h_{LV0}} \frac{p}{p^*(T)} \tag{8.14}$$

The technique of wet bulb temperature can be used even when water in the sling psychrometer freezes due to the evaporative cooling, with the corresponding change from h_{LV0}=2.5 MJ/kg to h_{SV0}=2.8 MJ/kg, in (8.13) and (8.14).

Humidity sensors

Early hygrometers used the elongation of some hygroscopic substances (notably long hair from a horse tail) with humidity. Hair consists of long keratin molecules coiled by bonds with cystine molecules, which loosen when adsorbing water. By the end of the 18th c., B. Saussure used very sophisticated hair hygrometers. Hygrometers based on artificial fibres are still used as simple humidity sensors.

The sling psychrometer and the dew-point method to measure humidity have been described above.

Nowadays, however, most humidity sensors are solid-state electric or electronic devices (notably thin-film dielectrics or semiconductors), for the ease of signal processing, and may be based on the electrical resistance or the electrical capacitance variation with humidity (e.g. a thermoset polymer between porous electrodes supplied in the kHz range, with on-chip silicon integrated voltage output signal conditioning). All electrical humidity sensors must have temperature compensation, their response is nearly proportional to relative humidity (not to humidity ratio) and the response time is typically half a minute. For very-low humidity measurement, as in semiconductor manufacturing atmospheres, spectral radiometric methods are used.

Primary humidity calibration is realised gravimetrically (by absorption on phosphorous pentoxide, P_2O_5, or magnesium perchlorate, $Mg(ClO_4)_2$), and secondary standards are based on enclosed saturated salt-water solutions (water content in the free humid-air space above, is only dependent on the type of salt; e.g. air at equilibrium with a NaCl-saturated aqueous solution has 75.3% RH at 20 ºC, with very small temperature variation; air with $BaCl_2$ reaches 90.3% RH, with $CaCl_2$ 29.0% RH, and with LiCl 11.1% RH); non-saturated salt-water solutions of given concentration may also be used (e.g. air in equilibrium with seawater has 98% RH), or other water solutions (e.g. a 50/50 in volume water / propylene glycol mixture reaches 70% RH); and appropriate mixtures of dry air and saturated air may be created.

Humidity indicators based on small desiccant pads with selective chemical additives that change colour at specific relative humidity are also used as simple visual indicators (several different additives may be impregnated on different desiccant pads on a same support, to provide a fine humidity scale).

PSYCHROMETRIC DIAGRAMS

Humid air formulation is not too complex (the highest burden being to compute adiabatic saturation temperatures), but a graphical display of data and processes is very helpful (to humans, not to computers) to better appreciate and transmit information. Because the variance of a gaseous humid-air system is V=3 as explained above, one of them must be fixed to make a two-dimensional diagram, and pressure is the best choice, since it is the less varying in practical circumstances.

Two different choices for the other two variables (besides pressure) were current in the 20th century: in the USA, temperature was chosen for abscissas and humidity ratio for ordinates, i.e. *w-T*, what is known as Carrier diagram in honour of the American engineer Willis Haviland Carrier (1876-1950), who in 1911 pioneered air conditioning, whereas in Europe humidity ratio was chosen for abscissas and enthalphy for ordinates, i.e. *h-w*, although not in rectangular but in oblique direction, what is known as Mollier diagram in honour of the German engineer (Austrian born) Richard Mollier (1863-1935) who in 1904 developed the steam diagram, and in 1923 the air/water diagram.

The *h-w* diagram is advantageous for graphical computations, since both variables are additive and solving mixing problems is just a straight line procedure in it. Lately, even the Carrier diagram was plotted in *w-h* variables instead of *w-T* (Fig. 8.2). However, nowadays that computers have replaced graphic calculations by hand, it seems an anachronism to keep to oblique *h-w* (or *w-h*) diagrams, and *T-w* or *w-T* diagrams serve the same for sketching humid-air processes.
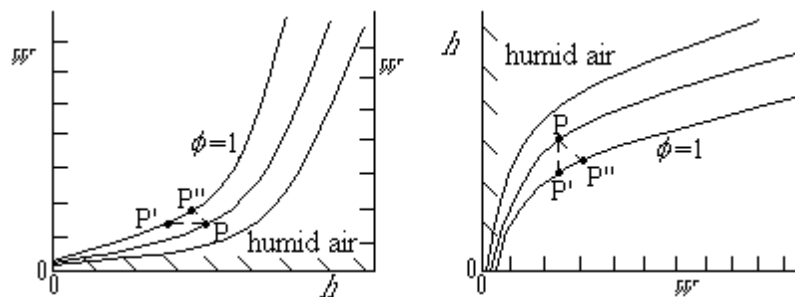

Fig. 8.2. Carriers's diagram and Mollier's diagram for humid air, showing one state P and its corresponding dew-point (P') and adiabatic-saturation point (P'').

As a visual exercise, the diagrams quickly show that, due to the curvature of the saturation line, the mixing of two nearly-saturated air streams may produce a supersaturated output.

Exercise 2. Adding water vapour to humid air

APPLICATIONS

Humid air processing may be applied to many engineering problems: drying-dehumidification, dehydration, moistening-humidification, demisting, defrosting, cooling, etc.

DRYING

Drying humid air is more often called dehumidification, and can be achieved by several means:
- By contact with a cold wall, below the dew point or frost point, where condensation takes place in a continuous way (if condensate drips off naturally, otherwise some defrosting is needed from time to time). This is the most common dehumidification procedure, but it is not very efficient because it cools the air too much (it often needs reheating), and requires a refrigerator, usually electrically-driven.
- By contact with a water-sorption material that is later regenerated by heating, either continuously in a rotating wheel, or intermittently in separate chambers. This procedure requires more expensive equipment than the former, but may operate with low-temperature heat (solar

heat or process-recovered heat). [Solid desiccants](#) and aqueous solutions of alkali halides are typical sorbent materials.

- By pressure changes, either isothermal compression, or adiabatic expansion. This procedure is too expensive and rarely used.

Drying is often understood to mean the process of getting out moisture from solid materials, i.e. to decrease water content in the surface and internal pores of a permeable solid substance. There are several methods to achieve drying:

- Exposure to physical desiccants, i.e. contact with another material, dryer; e.g. when we use a towel to dry our body, or a cloth to dry our dishes.
- Exposure to unsaturated air. This is the most common method of drying cloths, wood, food, etc.
- Exposure to chemical desiccants, i.e. hygroscopic materials like silica gel (the most used, it can reduce humidity down to 40% RH), calcium chloride...
- Exposure to vacuum. Lyophilisation is the total dehydration under high vacuum.
- Exposure to radiation (and a suitable absorber): e.g. sun rays, infrared lamps or microwaves.

Drying of materials is a mass transfer process and the driving force is the difference in chemical potential of water between the moist solid and the air. Mass transfer simply by diffusion is so slow that in all practical cases there is natural or forced convection dominating the mass transfer.

To make drying efficient, it is important to first let the material drain off, or even to mechanically squeeze, centrifuge, or wring it out.

Drying is enhanced by air flow, temperature difference, and dryness of the air, thus heating the air before coming into contact with the product is most common. Being a diffusion-controlled phenomenon, drying speed is proportional to exposed area. Drying by air may be in an open loop (the humidified air is replaced with fresh air) or in a close-loop by removing the water from the air by condensation in a refrigerator or by absorption with hygroscopic media (a desiccant, to be discarded or regenerated by heating it aside). When we dry our hands in a towel we do a similar buffer process: we transfer water from our hands to the towel, and hang it for further transfer of moisture to ambient air.

A quick moisture-measurement in some industries is based on pressure-measurement of the acetylene-gas generated in a closed vessel where a weighted sample is shaken with some calcium carbide.

Dehydration commonly refers to complete drying, as when all water in a food, an aqueous solution or an emulsion, is evaporated under the sun or in a kiln. Drying of food was the first food preservation method, followed by cooking and smoking, also in prehistoric times (later, curing with salt and spices, candying, canning, refrigeration and irradiation, were developed).

Notice that sometimes the drying or dehydration might cause chemical reactions in the product (to be accounted for in the energy balance).

HUMIDIFICATION

Moistening of materials is the process of making them holding more water in their surface or interior. It is usually accomplished by exposure to humid air, water mist, or even by water bathing. Notice that liquid water can be formed within porous media even at temperatures well above the dew point, because of depression caused by capillary effects.

Humidification of ambient air or any gas flow may be performed by directly adding water vapour (vaporisers), or by adding liquid water finely dispersed (sprayed, like in mechanical water-breakers and ultrasonic humidifiers); another way to humidify a gas is by combined drying of a wet material (e.g. a moisten wick blown with a fan). Steam generators consume much more energy and may cause burnings, whereas mechanical and ultrasonic humidifiers may throw away bacteria from stagnant water, and dissolved salts (producing dust). Air humidification in a small box, as used to keep cigars at around 70% RH, is performed by contact with an appropriate water solution; ambient air over a 50/50 propylene glycol / water solution gets saturated with 70% RH, so that if the air was drier some water evaporates, and if the air was more humid some vapour condenses (the very low vapour pressure of propylene glycol means that only water has to be added from time to time in dry climates).

A typical problem of humidification is to compute the amount of water to be added, and what happens when water is added in excess. In the later case, instead of one uniform flow, it is advisable to consider two flows: one saturated humid-air flow and one condensed flow, and establish the mass and energy balance accordingly. Mixing two unsaturated air streams at different temperatures may cause saturation, as warm moist air coming out of our mouth mixes with colder ambient air to yield a mist (the same phenomena may take place at the exhaust pipe of cars or aircraft; in the latter case they are called contrails, and may be so persistent as to develop in wide cirrus clouds and contribute to global warming).

Mass transfers in drying and humidifying always convey energy changes that may produce heating or cooling.

AIR CONDITIONING

Air conditioning, as its name implies, is getting the desired ambient-air properties from a different atmospheric condition, although it is sometimes synonymous of air refrigeration, since this is the toughest problem to solve in practice, heating being far easier to get than cooling (see Refrigeration).

Comfort is a subjective term of mental satisfaction with sensations from our nerve sensory system, and it is measured by parameters as 'percentage of satisfied individuals' from an exposed group. Thermal comfort depends a little on subjects (clothing habits), the environment (season), and interactions (occupation, previous accommodation). If we take as average comfort conditions T=20 ºC and ϕ=60%, the two usual problems are the summer problem of cooling and dehumidification, and the winter problem

of heating and humidification. For office work, temperatures above 24 ºC may cause unpleasant sweating, and below 19 ºC uncomfortable coldness. At around 25 ºC, metabolic heat release is fifty-fifty by water phase-change (transpiration and respiration) and by direct heat transfer (air convection and radiation), the ratio being in favour of the latter at colder temperatures (at 15 ºC, there is a 4:1 convection-to-transpiration ratio), and in favour of transpiration above 25 ºC.

A complete thermal scale to quantify human comfort may be: hypothermia, shivering, cold, cool, neutral, warm, hot, sweating, and heat stroke; the hypothalamus centre, at the base of the brain, tries to regulate body temperature to 37±1 ºC. A relative humidity above 70% may inhibit skin perspiration and promote microbial growth and odours, whereas below 30% dryness may cause respiratory infections and electrostatic shocks due to the reduction of the electrical conductivity of clothing and carpets. The comfort temperature range decreases as relative humidity increases, i.e. both hot and cold weather is more unbearable in humid climates (hot and humid, make us sweating a lot; cold and humid, spoils our dry-air heat-insulation layer close to our skin).

A curiosity related to relative humidity is why people lips get drier in cold weather, in spite of there being a higher relative humidity in the environment, the explanation being due to the local air heating by the body. There are other important local phenomena related to humid air, as the preferential dew over the moister leaves, or the preferential frost over car roofs (less radiant but less massive than the pavement), or why dew or frost forms first at the bottom of a vertical window pane (cold air sinks and cools further down).

The basic air-conditioning processes are shown in Fig. 8.3, and they are supplemented with 'recirculation', i.e. the partial mixing with ambient air in order to guarantee oxygen renewal and ventilation for living organisms. In most occasions, however, winter air-conditioning is substituted by simple heating, i.e. without further humidification, causing very dry working environments.
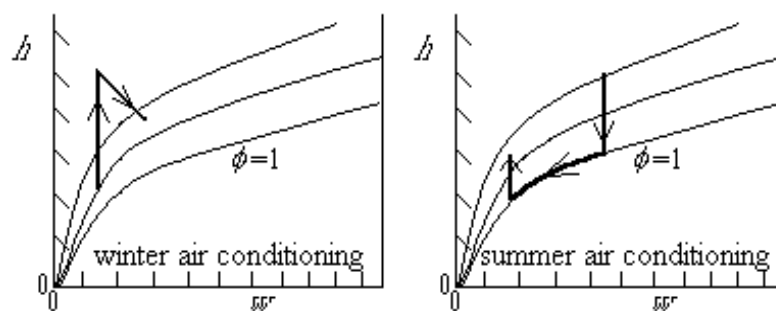

Fig. 8.3. Typical air conditioning processes in winter and summer.

A question in air conditioning of a room, as in any other steady process in a plenum, is how to define a representative state for the control volume system (that is not in equilibrium). Sometimes, the well-stirred room model is adopted, assuming that some forced convection in the interior will render nearly uniform properties all around (although obviously not near the inlet, however strong the stirring is). But in air conditioning applications it has been found to be better suited the one-dimensional model of linear variations between entry and exit conditions, and thus, the prevailing conditions in a room are defined as the arithmetic mean at the ends:

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$$h_{room} \equiv \frac{h_{in} + h_{out}}{2}, \quad w_{room} \equiv \frac{w_{in} + w_{out}}{2} \qquad (8.15)$$

Exercise 5. Summer air conditioning

Another name for generic air conditioning is 'climatisation', although the one most used in practice to refer to all the aspects is the acronym HVAC&R, which stands for Heating, Ventilation, Air Conditioning, and Refrigeration. Room heating may be as simple as a wood-fire, or as complex as a heat pump.

Ventilation

Ventilation, i.e. the renewal of ambient air, has several objectives:
- Sanitary renovation of breathable air in habitable spaces; i.e., removing foul air (contaminated with CO_2, odours and particles) and supplying fresh air, at a rate of at least 2 litres of fresh-air per second per person (10 L/s for smokers; ASHRAE-1989 standard was 7 L/s). Airliner standard cabin-air supply is 9.4 L/s per person (20 cfm), half fresh and half recycled (filtered).
- Convective cooling of living and powered systems; i.e., removing heat from any operating item (persons, animals, plants, electrical devices, chemical processes, and so on). The rate of ventilation depends on dissipated power and maximum allowed temperature.
- Convective entrainment of matter in air-consuming, vapour-generating and dust-generating processes, to keep operating the process; e.g. to keep a fire burning.

Ventilation can be achieved by different means:
- Natural ventilation caused by a density gradient in a gravity field. Density gradients can be due to a thermal gradient or a concentration gradient. The driving force is the pressure unbalance between the light and the heavy air columns: $\Delta p = \Delta \rho g L$. Notice the importance of the high of the air columns, L, what explains that the higher the chimney the stronger the draught. That is why it is better to have high windows should be higher than wider. This kind of ventilation is the best for health, the others causing too-much draught (in general, if an air current attracts our attention, then it is too much for comfort and may be a hazard to health).
- Natural ventilation caused by natural winds, either directly impinging on the object, or creating secondary air-currents by aerodynamic effects.
- Forced ventilation caused by a fan.

Notice that a person processes a minimum of $0.1 \cdot 10^{-3}$ kg/s of air in respiration, consuming a minimum of $5 \cdot 10^{-6}$ kg/s de O_2 and generating a minimum of $7 \cdot 10^{-6}$ kg/s de CO_2 and a minimum of $3 \cdot 10^{-6}$ kg/s de H_2O. Skin transpiration (perspiration) contributes in an even greater amount of H_2O. An adult at rest inhales 0.5 L of air twelve times per minute; air composition at inhalation is 77% N_2 + 21% O_2 + 1% H_2O + 1% Ar + 0.04% CO_2 (asphyxia is produced if $x_{O2} < 18\%$ for some time, by anoxia), whereas air composition at exhalation is roughly 77% N_2 + 16% O_2 + 3% H_2O + 1% Ar + 3% CO_2 (x_{CO2}=40 000 ppm in volume; normal respiration can be sustained in atmospheres with up to x_{CO2}=1000 ppm; fresh-air is assumed to

have x_{CO2}=380 ppm, but in large-city centres it might reach double concentration). The intake varies from 0.5 L to 2 L on deep gasps, and the rate varies from 12 breath/min at rest to 120 breath/min on panting.

Facing even its own name, air conditioning is blamed as one of the major focus of contamination for indoor air, mainly because air conditioning installations stir dust (may be prevented with good filters that remove polluting airborne particles, and proper filter cleaning), and because they are a perfect breeding place for pathogen micro-organisms.

Demisting

Demisting (or defogging) is the process of getting rid of water-condensation in liquid form (as droplets or a film), usually on solid surfaces (but may be also a bulk effect), through evaporation produced by heating the surface or by blowing dry air; other means to get rid of condensation is by mechanical wiping.

Condensation in the indoor side of a window may take place when the interface falls below the dew-point temperature in the room, usually by moisture generated by occupants. Condensation must be avoided not just to have a clear view, but because it damages window frames, sills, the surrounding paint, wallpaper, plasterboard, etc. When condensation cannot be avoided (as in bathrooms and kitchens) supplementary ventilation (e.g. exhaust fans) and water-proof walls should be used. Double glazing usually prevents condensation by not allowing the indoor interface to become too cold (condensation might occur within the double pane if the seal around is broken, or in the outdoors interface, but this requires the panes to be colder than the air around, as in the next example.

Condensation in the outdoor side of a window, as in street-parked cars at dawn, may take place when that interface is colder than the surrounding air, in this case by radiation to a colder far object, as the night sky at dawn in clear nights following a warm day. Condensation in the outdoor side of a window is more difficult to happen on living spaces.

Although it might seem preferable to blow hot air for demisting, sometimes it is better to blow cold (refrigerated) air, as when getting rid of condensation in the inside of car windscreen, because, in spite of hot air being able to dissolve more water and increase evaporation, the much lower humidity ratio of cool air (being dehumidified in the air-conditioner), more than compensates the adverse effect of a lesser temperature gradient; even more, the best to demist car windows is to run at the same time the air conditioning (to get rid of water) and the heater (to keep a comfortable temperature). Notice that demisting car interiors is a prolonged requirement, aggravated by passengers' transpiration and respiration, whereas demisting and defrosting car outsides is a one-time activity before people being inside.

Defrosting

Defrosting (or de-icing) is the process of getting rid of water-condensation in solid form, i.e. as ice crystals or an ice sheet, usually on solid surfaces. Frosting must be eliminated in vaporisers of refrigeration equipment because they increase thermal resistance (see Refrigeration), in car windscreen to

be able to see through, in airplanes to avoid losing lift and control, in streets and footpaths to avoid accidents, and so on.

Defrosting can be achieved by thermal means (basically by heating the interface, since blowing hot air is very inefficient), by mechanical means (handheld scrapers), or by chemical means (as when salt is added to melt ice on the streets). Mechanical scrapers may damage the substrate surface; the best to detach the ice sheet is to first eliminate the ice bonding at the interface by local heating, and then mechanically remove the ice layer with care.

Sometimes, the same set-up is used for defrosting and demisting, as the electrical surface heater in car rear windows, usually made of a wire mesh, hot-glued to the inside, consuming some 200 W, and reaching some 30 ℃ of temperature increment.

EVAPORATIVE COOLING

It is known that all industrial processes, as all living organisms, need to get rid of waste heat to be in a steady state (entropy generation must be balanced by entropy flow outwards). For airborne industries and living beings, the heat must flow to the surrounding air, but air is a thermal insulator, and, although blowing air enhances the transfer by one or two orders of magnitude, it is not enough in some circumstances, but nature showed us an ultimate resource: evaporative cooling.

Evaporative cooling is the most common refrigeration effect on nature: water in contact with unsaturated air, tends to evaporate, and the associated vaporisation enthalpy is withdrawn from the contacting media (water and air). There are numerous applications of this principle in nature and technology:
- Our sweating is a most efficient body-cooling means. Notice that there is some water spent in evaporative cooling, i.e. loosing part of the body to protect the rest (a mild form of ablation). Many other animals rely on sweeting glands in their skin for their thermal control (but dogs rely on blowing air along their tongue, elephants on moving their large ears...).
- Plants transpire water through pores in their leaves called stomata, lowering temperature locally (that is why dew and frost form early over grass than over bare soil).
- Splashing water on the floor in hot-and-dry climates must have been used since Prehistoric times to provide some kind of local air conditioning.
- Holding water in earthenware pots (porous fired clay portable container with a handle and two openings, Spanish *botijo*) has been used to produce chill water since ancient Mesopotamian times.
- Portable refrigeration devices not requiring fluid pipes through room walls, based on evaporative cooling, are in the market (their performances are not comparable to standard refrigerators with moisture removal).
- Most cryogenic vessels (cryostats) use the boil-off vapour as a cooling aid (cryostats are open vessels to avoid pressure rising to unacceptable levels).
- Spacecraft with compact surface, short mission duration, and large heat-release needs, also make use of evaporative cooling for their thermal control (e.g. in Apollo missions for the command module, lunar module, and portable life support system).

The main drawbacks of evaporative cooling are:

- Humidity increases in the surrounding air, so that, if moisten air is not blown away, the cooling effect decreases with time.
- Cooling power is small because water has a small vapour pressure at room conditions (more volatile liquids produce stronger cooling, but are too expensive to be discarded). Cooling power may be large, however, in the special configurations of cooling towers presented below.
- Water must be supplied, and, if not distilled, solid deposits may form, bacteria will grow, etc.
- The high humidity air may cause problems beyond the decreasing refrigeration effect; e.g. it may condense and promote corrosion and spoilage, forms mist plumes in cooling towers, etc.

Cooling towers

An important industrial application of evaporative cooling is the direct-contact heat-exchanger known as cooling tower or wet tower, a device to get rid of heat from another system which is cooled by a water stream (much more efficiently than air cooling; four or five orders of magnitude more than natural convection in air). In a cooling tower, the water to be cooled is finely dispersed over an upcoming stream of air; what causes some water evaporation and the consequent cooling of the remaining water (that provides the vaporisation enthalpy).

The flow of water is always forced with an external pump, and the flow of air usually forced with a fan in the cooling tower, although in the largest cooling towers (those of large power stations) air circulation is by natural convection. Inside the tower, a high-porosity solid fill (e.g. made of plates or honeycombs) enhances mass transfer between water and air by extending water-droplet surface and increasing residence time. In most cooling towers both streams are vertical and counter-flow, but cross-flow towers, where air is laterally aspirated (perpendicular to the falling water stream) are also used.

The huge cooling towers used in nuclear power plants are able to transfer more than 1000 MW from water to air; they are up to 200 m high and 100 m in diameter, with a typical hyperboloid shape for maximum structural strength, not for thermal purposes. The tower is just an empty chimney, since the filling is only 3 m high and just above the ground-level air-openings, with 0.2 m thick walls made of steel-reinforced concrete; the main working load is its own weight, that with this shape results in stresses being transmitted down two diagonal straight-lines (hyperboloid construction) instead of just one (cylindrical construction). In those high chimneys, vertical variations of ambient temperature should be accounted for (±5 ºC typically, favourable during daytime and detrimental during nighttimes temperature inversion).

The water that is cooled by evaporation in a cooling tower may be already the cooling liquid of the main system to cool, or it may be an intermediate loop that cools another loop (of water or not), as shown in Fig. 8.4.
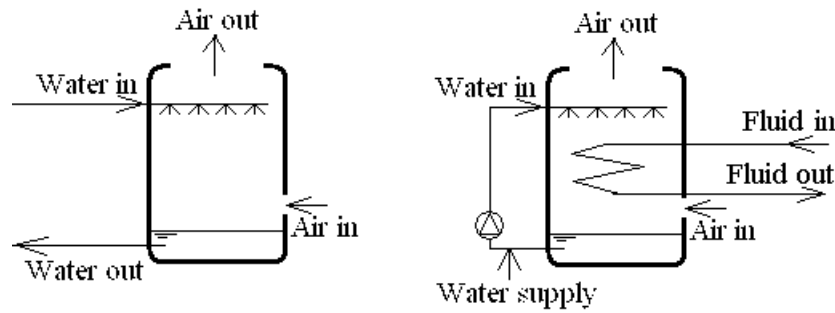
Fig. 8.4. Cooling towers: simple (left) and 'closed' (right). Only the flows are indicated; other vital components, as the fan to force the air flow, the filling to enhance mass transfer, and the drop scrubbers to minimise water losses, are not shown.

Notice that, in most humid air applications, one relies on gravity to separate water droplets from the air (e.g. in cooling towers), but small drops do not easily fall, particularly in an upward air stream as in cooling towers, so that inertial filters are currently part of humid air installations.

Exercise 6. Cooling tower

ADIABATIC COOLING IN THE EARTH'S ATMOSPHERE

A natural humid-air phenomenon is considered here: the adiabatic cooling in the Earth atmosphere of an ascending air mass due to pressure decreasing. The Earth atmosphere is in unstable equilibrium because it is heated from below in a gravity field (because air is largely transparent to radiation from the Sun, that is absorbed at the ground and water surface), giving way to winds that, by the effect of the uneven heating and the Coriolis force due to Earth rotation, give way to the General Atmospheric Circulation (Trade winds, Hadley Cell, and so on).

An averaged temperature profile with height is found experimentally and called the Standard Atmosphere, with −6.5 ºC/km from sea level to 11 km and constant temperature from there to 20 km. It is in this lowest part of the atmosphere (the troposphere, 11 km in the average, but varying from 9 km in the Poles to 18 km in some parts of the Equator), that the majority of meteorological processes take place.

It is amazing that the major part of the mass and energy balance of the Atmosphere is governed by a minority component, water vapour, that never goes over 4% in molar fraction and its average is less than 0.01%. In fact, the major constituents of air, N_2 and O_2 keep their relative proportion everywhere in the Atmosphere, whereas the concentration of H_2O decreases exponentially 1000 times from 0 to 11 km (it remains more or less constant upwards due to methane oxidation); more than half of the whole H_2O in the Atmosphere is in the lowest 250 m over sea level. The answer to this key role lies precisely in the limited solubility of H_2O in air and its dependence on temperature, that forces condensation as the air ascends and cools, and precipitation in the gravity field. Paradoxical, however, is the fact that there is more H_2O dissolved in the air than there is liquid water in the heaviest rainfall; the heaviest rain very rarely surpasses 120 mm/hour ($33 \cdot 10^{-3}$ kg/(s·m^2)), what, at an speed of 5 m/s means $7 \cdot 10^{-3}$ kg/m^3 of liquid, against some $30 \cdot 10^{-3}$ kg/m^3 of saturated vapour in the air (depending on the temperature).

We precisely want to know how fast ascending-air cools, i.e. the adiabatic gradient $\Gamma \equiv -dT/dz$, assuming negligible heat transfer, and to compare it with the Standard Atmosphere gradient of -6.5 ºC/km. Neglecting also frictional losses, the rise may be modelled as isentropic and thus:

$$\frac{dT}{T} = \frac{\gamma - 1}{\gamma}\frac{dp}{p}, \quad \frac{dp}{dz} = -\rho g = -\frac{p}{RT}g, \quad \Rightarrow \quad \Gamma \equiv -\frac{dT}{dz} = -\frac{g}{c_p} = -9.8 \text{ K/km} \qquad (8.16)$$

i.e. it cools faster than the standard, its density would be higher, and then it would fall, thus a stable situation Instabilities may come from two modifications in the model just described. First, the actual gradient (called geometric gradient) may depart a lot from the average of -6.5 ºC/km, but a second (and more important) cause is that no condensation was envisaged in (8.16); if the air has enough vapour to get saturated and condense, the isentropic model is no longer valid, and the adiabatic gradient drops to nearly half, making the rise unstable (during condensation, the latent enthalpy is released, reducing the density and forcing subsequent rise).

As mentioned above, vapour condensation in humid air requires some supersaturation, usually from air cooling during an ascent (updraught), what gives way to cloud formation and growth. Precipitation takes place when the droplets or ice crystals are large enough for the fall in potential energy to overcome the decrease in entropy of mixing (i.e., when $|dH| > |TdS|$ in $dG = dH - TdS$); notice that, for the precipitation particles to reach macroscopic size, an updraught that overcomes the falling terminal velocity is required to keep the particles suspended for enough time to grow (it is a slow process of accretion).

TYPE OF PROBLEMS

Besides housekeeping problems of how to deduce one particular equation from others, the types of problems in this chapter are:

1. Find the saturation point of humid air when one variable may be changed (adding vapour at T and p constant, cooling at p and w constant, expanding at T and w constant).
2. Converting from one composition variable to others (e.g. from wet bulb temperature to dew point temperature).
3. Find the new state after some process (drying, humidification, mixing of two air streams, air conditioning).
4. Solving cooling tower mass and energy balances.