

DRYING

...by vaporizing the water that is contained in the paper (solid) - latent heat of vaporization must be supplied.

Two important process-controlling factors:

- (a) transfer of heat to provide the necessary latent heat of vaporization,
- (b) movement of water or water vapor through the paper network and then away from it to effect separation of water

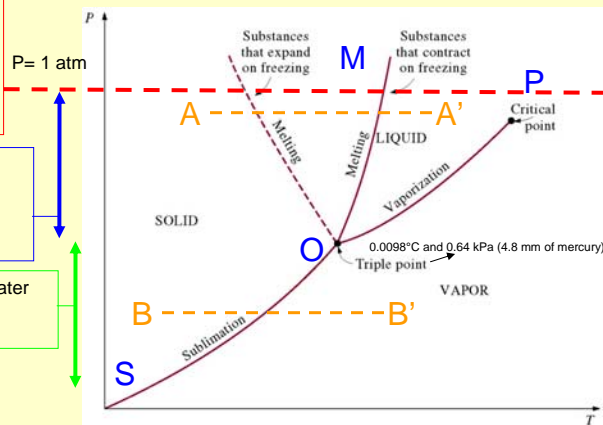
BASIC DRYING THEORY

review

Air and contact drying: heat is transferred through the material from heated air or from heated surfaces. The water vapor is removed with the air

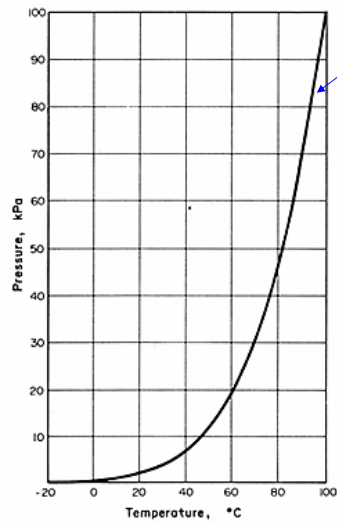
Vacuum drying: evaporation of water occurs more readily at lower P

Freeze drying: the water vapor is sublimed off frozen material



Phase diagram for, e.g., water

review



The **vapor pressure/temperature curve** for water.

Vapor pressure is the measure of the tendency of molecules to escape as a gas from the liquid.

Boiling occurs when the $P^v = P^T$.

review

Heat Requirements for Vaporization

↓ **latent heat of vaporization** $\Delta H^v = \Delta H^v(\underline{T}, P)$
energy required per kg of water

↓ **latent heat of sublimation**

↓ Steam tables.

EXAMPLE. Heat energy in air drying

Fibrous material containing 80% water is to be dried at 100°C down to moisture content of 10%. If the initial temperature of the material is 21°C, calculate the quantity of heat energy required per unit weight of the original material, for drying under atmospheric pressure. The latent heat of vaporization of water at 100°C at standard atmospheric pressure is 2257 kJ kg⁻¹. The specific heat capacity of the material is 3.8 kJ kg⁻¹ °C⁻¹ and of water is 4.186 kJ kg⁻¹ °C⁻¹. Find also the energy requirement/kg water removed.

Calculating for 1 kg of initial wet material: $(100 \times 200)/900 \text{ g} = 22.2 \text{ g}$ final moisture associated with 200 g dry matter.

1 kg of original matter must lose $(800 - 22) \text{ g moisture} = 778 \text{ g} = 0.778 \text{ kg moisture}$.

Heat energy required for 1kg original material

= heat energy to raise T to 100°C + latent heat to remove water
 = $(100 - 21) \times 3.8 + 0.778 \times 2257 = 300.2 + 1755.9 = \underline{2056 \text{ kJ}}$

Energy/kg water removed, as 2056 kJ are required to remove 0.778 kg of water = $2056/0.778 = \underline{2643 \text{ kJ}}$.

Steam - to supply heat to air or to surfaces used for drying.

↘ In condensing, steam gives up its latent heat of vaporization

In drying, the substance being dried must take up latent heat of vaporization to convert its liquid into vapor

Ideally:

~~1 kg of steam condensing will produce 1 kg vapor.~~


- Steam and the material will in general be under \neq P:

(material at lower P → higher ΔH^{vap}) ΔH^{vap}

- Heat losses and sensible heat changes

LATENT HEAT AND SATURATION TEMPERATURE OF WATER

Absolute pressure (kPa)	Latent heat of vaporization (kJ kg ⁻¹)	Saturation temperature (°C)
1	2485	7
2	2460	18
5	2424	33
10	2393	46
20	2358	60
50	2305	81
100	2258	99.6
101.35 (1 atm)	2257	100
110	2251	102
120	2244	105
200	2202	120
500	2109	152



EXAMPLE. Heat energy in vacuum drying

Using the same material as in previous example, if **vacuum drying** is to be carried out at **60°C** under the corresponding saturation pressure of 20 kPa abs. (or a vacuum of 81.4 kPa), calculate the heat energy required to remove the moisture per unit weight of raw material.

Heat energy required per kg raw material

= **heat energy to raise temperature to 60°C + latent heat of vaporization**
 at 20 kPa abs = $(60 - 21) \times 3.8 + 0.778 \times 2358 = 148.2 + 1834.5 = \underline{1983 \text{ kJ}}$.

In freeze drying the latent heat of sublimation must be supplied. Pressure has little effect on the latent heat of sublimation, which can be taken as **2838 kJ kg⁻¹ (2643 kJ kg⁻¹ @ P_{atm})**.

EXAMPLE. Heat energy in freeze drying

If the material in the two previous examples were to be **freeze dried** at **0°C**, how much energy would be required per kg of raw material, starting **from frozen solid at 0°C**?

Heat energy required per kilogram of raw material = **latent heat of sublimation** = $0.778 \times 2838 = \underline{2208 \text{ kJ}}$.

Heat Transfer in Drying

Rates of drying → determined by the **rates at which heat energy can be transferred** to the water.

→ Conduction, radiation and convection

Sometimes the rate of mass transfer (removal of the water) can be limiting.

In **air drying** the rate of heat transfer is

$$q = h_s A (T_a - T_s)$$

q J s⁻¹
 h_s surface heat-transfer coefficient J m⁻² s⁻¹ °C⁻¹,
 A area, m²
 T_a air temperature
 T_s temperature of the surface

In a **roller dryer** where moist material is spread over the surface of a heated drum

conduction → $q = UA(T_i - T_s)$

U is the overall heat-transfer coefficient

T_i is the drum temperature (close to that of the steam)

T_s is the surface temperature of the material (boiling point of water or slightly above)

A is the area of drying surface on the drum.

U can be estimated from the conductivity of the drum material and of the layer of material.

U as high as **1800 J m⁻² s⁻¹ °C⁻¹** under very good conditions and down to about **60 J m⁻² s⁻¹ °C⁻¹** under poor conditions.

Radiation

surface temperature of the material may be higher than the air temperature.

Freeze drying

the heat transfer occurs mainly by conduction.

As drying proceeds

Dry material begins to occupy the surface layers and conduction must take place through these **dry surface layers which are poor heat conductors** so that heat is transferred to the drying region progressively more slowly.

Dryer Efficiencies

Efficiency calculations are

- useful when assessing the performance of a dryer,
- in making comparisons

Ratio of the minimum energy needed to the energy actually consumed.

Other efficiency measures can be worked out

1. One measure of efficiency is the ratio of the **minimum quantity of heat that will remove the required water** to the **energy actually provided for the process**. Sensible heat can also be added to the minimum, as this added heat in the material often cannot be economically recovered.

2. For air drying (e.g., spray dryers): a heat balance over the air, **treating the dryer as adiabatic** (with no exchange of heat with the surroundings). Then the **useful heat transferred to the material for its drying corresponds to the drop in temperature in the drying air**, and the **heat which has to be supplied corresponds to the rise of temperature of the air in the air heater**.

$$\eta = (T_1 - T_2) / (T_1 - T_a)$$

T_1 is the inlet (high) **air** temperature **into the dryer**

T_2 is the outlet **air** temperature **from the dryer**

T_a is the **ambient air** temperature.

EXAMPLE. Efficiency of a pulp dryer

A dryer reduces the moisture content of 100 kg of a pulp product from 80% to 10% moisture. 250 kg of steam at 70 kPa gauge is used to heat 49,800 m³ of air to 80°C, and the air is cooled to 71°C in passing through the dryer. Calculate the efficiency of the dryer. The specific heat of this pulp is 3.43 kJ kg⁻¹ °C⁻¹. Assume the pulp enters at 24°C, which is also the ambient air temperature, and leaves at the same T as the exit air.

In **100 kg of raw** material there is 80% moisture, that is 80 kg water and 20 kg dry material,

total weight of dry product = 20 x (10/9) = 22.2 kg

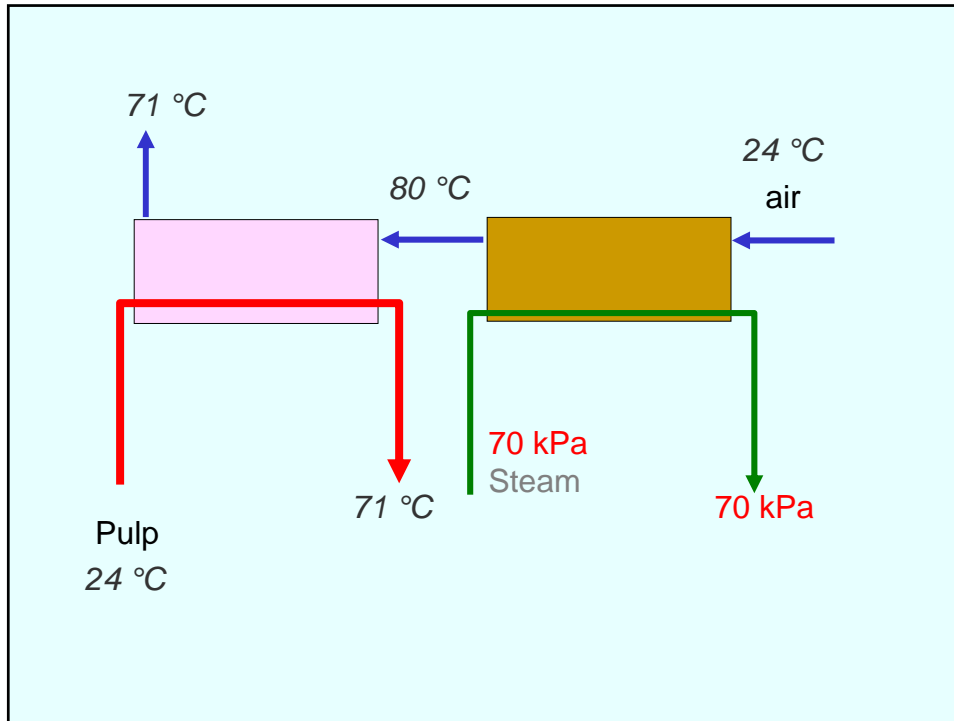
weight of water = (22.2 - 20) = 2.2 kg.

water removed = (80 - 2.2) = 77.8 kg.

Heat supplied to pulp product

= *sensible heat to raise the product temperature from 24°C to 71°C + latent heat of vaporization.*

Now, the latent **heat of vaporization corresponding to a saturation temperature of 71°C is 2331 kJ kg⁻¹**



Heat (minimum) supplied/100 kg pulp

$$= 100 \times (71 - 24) \times 3.43 + 77.8 \times 2331$$

$$= 16 \times 10^3 + 181 \times 10^3 = 1.97 \times 10^5 \text{ kJ.}$$

Heat to evaporate water only = $77.8 \times 2331 = 1.81 \times 10^5 \text{ kJ}$

The specific heat of air is $1.0 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$ and the density of air is 1.06 kg m^{-3}

Heat given up by air/100 kg pulp

$$= 1.0 \times (80 - 71) \times 49,800 \times 1.06 = 4.75 \times 10^5 \text{ kJ.}$$

The latent heat of steam at 70 kPa gauge is 2283 kJ kg^{-1}

$$\text{Heat in steam} = 250 \times 2283 = 5.71 \times 10^5 \text{ kJ.}$$

(a) efficiency based on latent heat of vaporization only:

$$= (1.81 \times 10^5) / (5.71 \times 10^5) = 32\%$$

(b) efficiency assuming sensible heat remaining in pulp after drying is unavailable

$$= (1.97 \times 10^5) / (5.71 \times 10^5) = 36\%$$

(c) efficiency based heat input and output, in drying air

$$= (80 - 71) / (80 - 24) = 16\%$$

Note the **advantages gained by operating at the highest feasible air inlet temperature and the lowest air outlet temperatures.**

Examples of overall thermal efficiencies are:

drum dryers 35-80%

spray dryers 20-50%

radiant dryers 30-40%

After sufficient energy has been provided to vaporize or to sublime moisture from the material, **some way must be found to remove this moisture:**

In freeze-drying and vacuum systems → condense the water to a liquid or a solid and then the vacuum pumps have to handle only the non-condensable gases.

In atmospheric drying → a current of air is used.

MASS TRANSFER IN DRYING

Heat transfer → driving force = ΔT

Rate of heat transfer ~ potential of T, U.

Mass is transferred under the driving force provided by a partial pressure or concentration difference. The rate of mass transfer is proportional to the potential (pressure or concentration) difference and to the properties of the transfer system characterized by a mass-transfer coefficient.

Analogous to $q = UA \Delta T...$

$$dw/dt = k'_g A \Delta Y$$

the humidity in kg kg^{-1}
area through which the transfer is
taking place
mass-transfer coefficient, $\text{kg m}^{-2} \text{s}^{-1}$
mass being transferred, kg s^{-1}

not as straightforward as heat transfer...

Why?

Because the movement pattern of moisture changes as drying proceeds:

Initially, the mass (moisture) is transferred from the surface of the material and later, to an increasing extent, from deeper within the material (eg, paper) to the surface and therefore to the air.

So the first stage is to determine the relationships between the moist surface and the ambient air and then to consider the diffusion through the material.

In studying the surface/air relationships, it is necessary to consider mass and heat transfer simultaneously.

PSYCHROMETRY

The **capacity of air for moisture removal** depends on its **humidity** and its **temperature**.

Humidity (Y) is the measure of the **water content of the air**.

The **absolute humidity** (the humidity ratio)
mass of water vapor per unit mass of dry air
(kg kg^{-1}) = humidity.

Air:

Saturated with water vapor at a given temperature and pressure **if its humidity is a maximum under these conditions**. *The partial pressure of the water vapor in the air is equal to the saturation vapor pressure of water at that temperature.*

If further **water is added** to saturated air, it must appear as liquid water in the form of a **mist or droplets**.

The total pressure of a gaseous mixture, such as air and water vapor, is made up from the sum of the **partial pressures** (molar concentration of the constituents)

EXAMPLE. Partial pressure of water vapor

If the total pressure of moist air is 100 kPa (approximately atmospheric) and the humidity is measured as 0.03 kg kg⁻¹, calculate the partial pressure of the water vapor.

The molecular weight of air is 29, and of water 18

So the mole fraction of water = $(0.03/18)/(1.00/29 + 0.03/18)$
= $0.0017/(0.034 + 0.0017) = 0.048$

Therefore the water vapor pressure p_w

$$p_w = yP = 0.048 \times 100 \text{ kPa} = \underline{4.8 \text{ kPa.}}$$

Mole fraction

Relative humidity (RH)

The ratio of the partial pressure of the water vapor in the air (p) to the partial pressure of saturated water vapor at the same temperature (p_s). Therefore:

$$RH = p_w/p_s$$

and is often expressed as a percentage

$$= 100 p_w/p_s$$

EXAMPLE. Relative humidity

If the air in the previous is at 60°C, calculate the relative humidity.

From steam tables, the saturation pressure of water vapor at 60°C is 19.9 kPa.

$$\begin{aligned}\text{Therefore the relative humidity} &= p/p_s \\ &= 4.8/19.9 \\ &= 0.24 \\ &\text{or } \underline{24\%}.\end{aligned}$$

If such air were cooled, then when the percentage relative humidity reached 100% the air would be saturated and this would occur at **that temperature** at which $p = p_s = 4.8$ kPa.

Interpolating from the steam tables, or reading from the water vapor P-T graph, this occurs at a temperature of 32°C and this temperature is called the **dew point** of the air at this particular moisture content.

If cooled below the dew point: water condenses out (fog), and the water remaining as vapor in the air will be that corresponding to saturation at the temperature reached.

The **humidity Y** can be related to the partial pressure p_w of the water vapor in air by the equation:

$$Y = 18 p_w / [29(P - p_w)]$$

where P is the total pressure.

In circumstances where p_w is small compared with P , and this is approximately the case in air/water systems at room temperatures, $Y \approx 18p_w/29P$

Humid heat, c_s of moist air J kg⁻¹ °C⁻¹ -

...Is based only on the mass of the dry air

The enthalpy change = mass of dry air multiplied by the temperature difference and by the humid heat.

Read off a psychrometric chart.

The specific heat of the water it contains is effectively incorporated into the humid heat

Wet-bulb Temperatures

...as compared with the ordinary temperature (the **dry-bulb temperature**)

Wet-bulb Temperature is the temperature reached by a water surface, such as that registered by a thermometer bulb surrounded by a wet wick, when exposed to air passing over it. The wick and therefore the thermometer bulb decreases in temperature below the dry-bulb temperature until the rate of heat transfer from the warmer air to the wick is just the needed to provide for the evaporation of water from the wick into the air stream.

$$h_c A (T_a - T_s) = \lambda k'_g A (Y_s - Y_a)$$

a and s denote actual and saturation temperatures and humidities

h_c is the heat-transfer coefficient

k'_g the mass transfer coefficient from the air to the wick surface

λ is the latent heat of evaporation of water.

When the air is saturated, the wet-bulb temperature and the dry-bulb temperature are identical.

$(T_a - T_s)$ is plotted against $(Y_s - Y_a)$,

the point (T_s, Y_s) must correspond to a dew-point condition

we then have a wet-bulb straight line on a temperature/humidity chart sloping down from the point (T_s, Y_s) with a slope of:

$$(T_a - T_s)/(Y_s - Y_a) = (\lambda k'_g/h_c)$$

Adiabatic saturation line. Water in contact with humid air: both ultimately reach a temperature at which the heat lost by the humid air on cooling is equal to the heat of evaporation of the water leaving the stream of water by evaporation.

Under this condition with no heat exchange to the surroundings, the total enthalpy change (kJ kg⁻¹ dry air)

$$\Delta H = c_s(T_a - T_s) + \lambda(Y_s - Y_a) = 0$$

$$c_s = -\lambda(Y_s - Y_a)/(T_a - T_s) \quad , \quad (Y_s - Y_a)/(T_a - T_s) = (h_c/\lambda k'_g)$$

$$c_s = -h_c/k''_g$$

where c_s is the humid heat of the air.

Now it just so happens, for the water/air system at normal working temperatures and pressures that for practical purposes the numerical magnitude of the ratio:

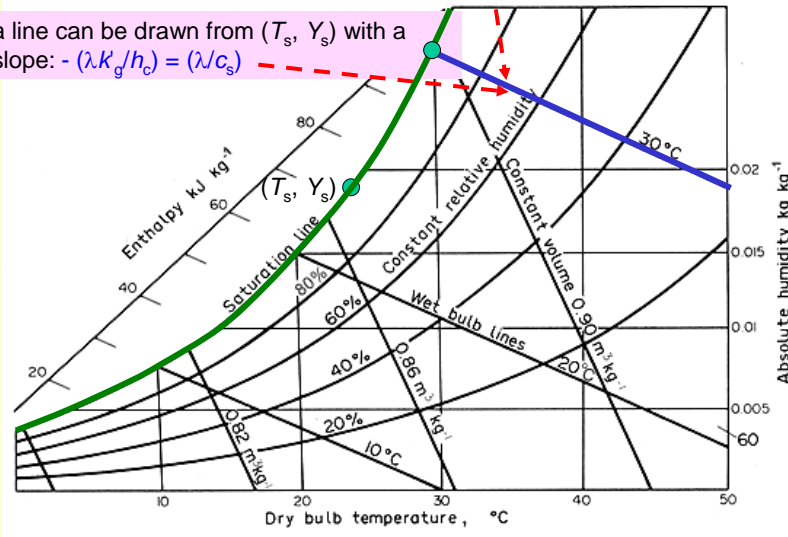
$$c_s = -h_c/k''_g \text{ (known as the Lewis number)} \approx 1$$

This has a useful practical consequence. The wet bulb line and the adiabatic saturation line coincide when the Lewis number = 1.

Psychrometric Chart

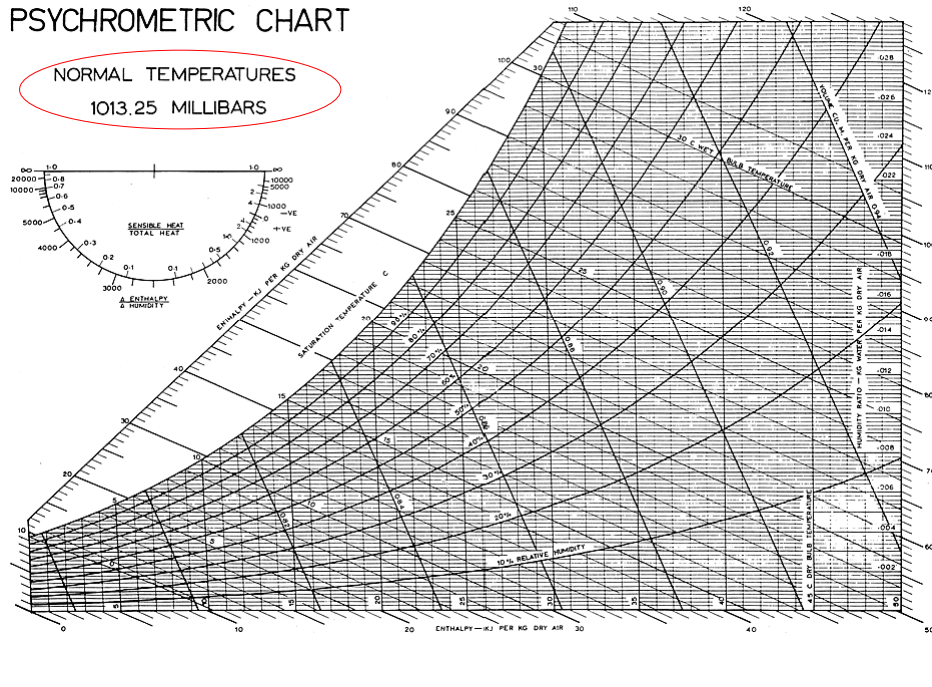
wet bulb or adiabatic cooling line

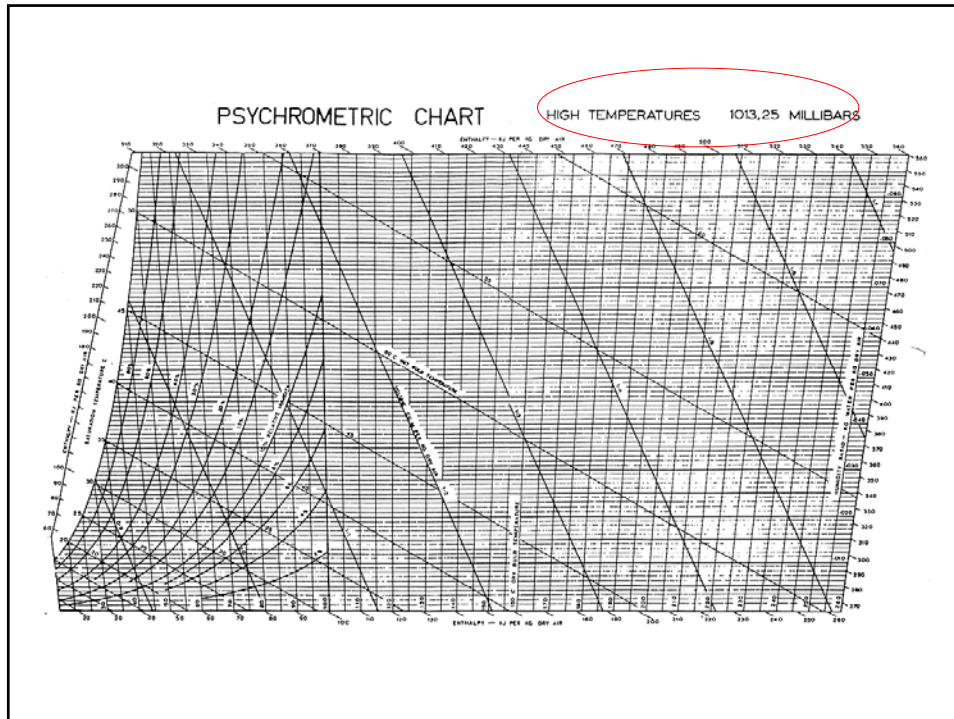
a line can be drawn from (T_s, Y_s) with a slope: $-(\lambda k'_g/h_c) = (\lambda/c_s)$



PSYCHROMETRIC CHART

NORMAL TEMPERATURES
1013.25 MILLIBARS



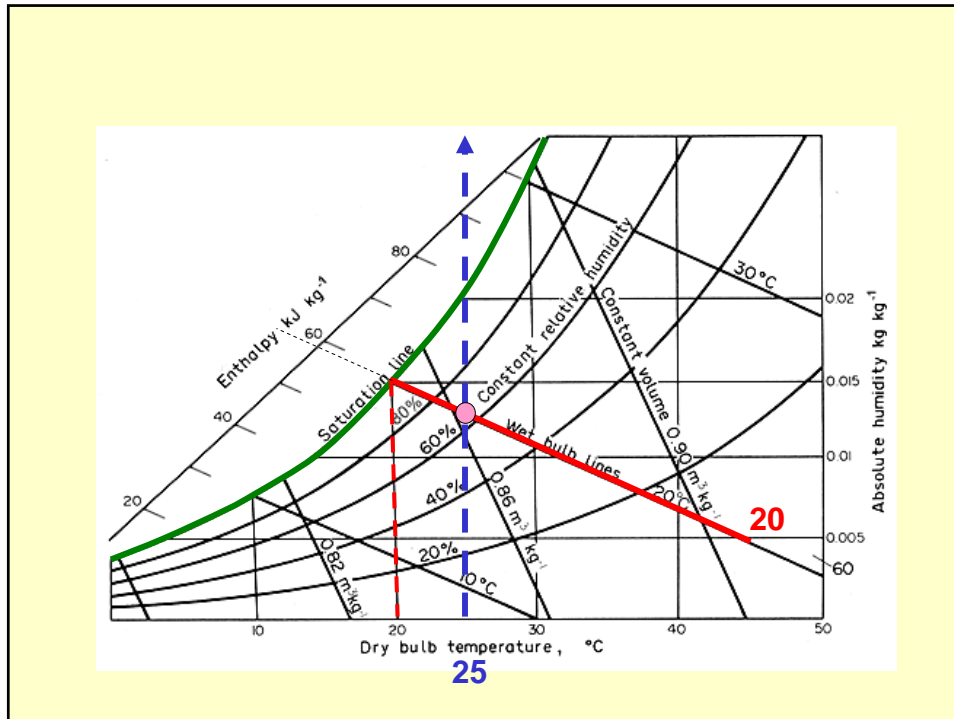


EXAMPLE. Relative humidity, enthalpy and specific volume of air

If the wet-bulb temperature in a particular room is measured and found to be 20°C in air whose dry-bulb temperature is 25°C (that is the wet-bulb depression is 5°C) estimate the relative humidity, the enthalpy and the specific volume of the air in the room.

On the humidity chart follow down the wet-bulb line for a temperature of 20° until it meets the dry-bulb temperature line for 25°C. Examining the location of this point of intersection with reference to the lines of constant relative humidity, it lies between 60% and 70% RH and about 4/10 of the way between them but nearer to the 60% line. Therefore the RH is estimated to be 64%. Similar examination of the enthalpy lines gives an estimated enthalpy of 57 kJ kg⁻¹, and from the volume lines a specific volume of 0.862 m³ kg⁻¹.

Once the properties of the air have been determined other calculations can easily be made.



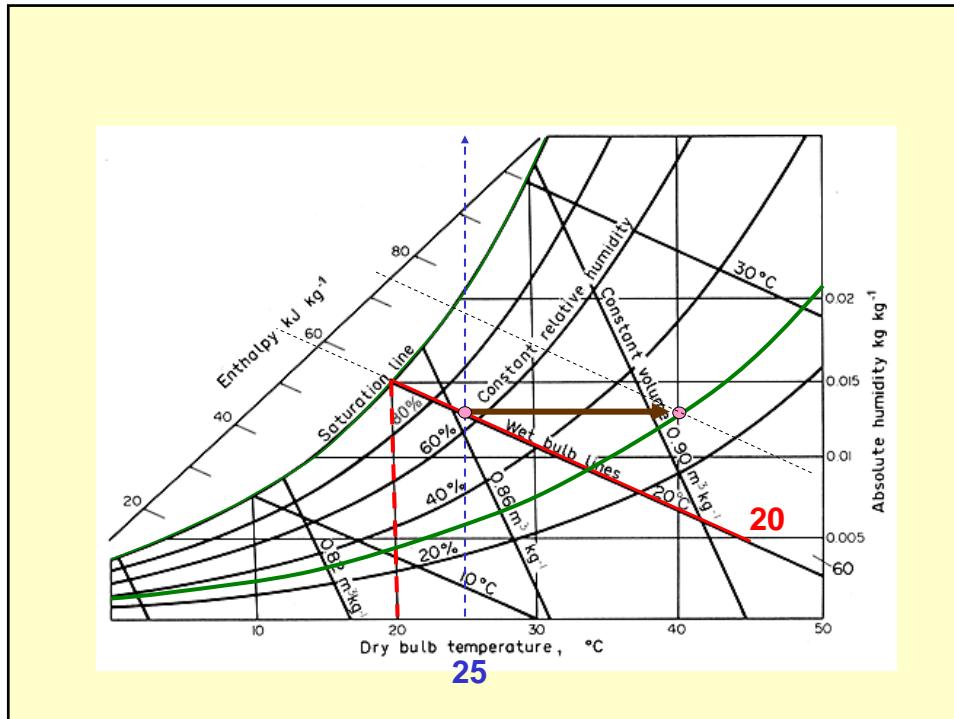
EXAMPLE. Relative humidity of heated air

If the air in previous example is then to be heated to a dry-bulb temperature of 40°C, calculate the rate of heat supply needed for a flow of 1000 m³ h⁻¹ of this hot air for a dryer, and the relative humidity of the heated air.

On heating, the air condition moves, at constant absolute humidity as no water vapor is added or subtracted, to the condition at the higher (dry bulb) temperature of 40°C. At this condition, reading from the chart at 40°C and humidity 0.0125 kg kg⁻¹, the enthalpy is 73 kJ kg⁻¹, specific volume is 0.906 m³ kg⁻¹ and RH 27%.

Mass of 1000 m³ is $1000/0.906 = 1104\text{kg}$, $\Delta H = (73 - 57) = 16 \text{ kJ kg}^{-1}$.
Rate of heating required = $1104 \times 16 \text{ kJ h}^{-1} = (1104 \times 16)/3600 \text{ kJ s}^{-1} = \underline{5 \text{ kW}}$

If the air is used for drying, with the heat for evaporation being supplied by the hot air passing over a wet solid surface, the system behaves like the adiabatic saturation system. It is adiabatic because no heat is obtained from any source external to the air and the wet solid, and the latent heat of evaporation must be obtained by cooling the hot air. Looked at from the viewpoint of the solid, this is a drying process; from the viewpoint of the air it is humidification.



EXAMPLE. Water removed in air drying

Air at 60°C and 8% RH is blown through a continuous dryer from which it emerges at a temperature of 35°C. Estimate the quantity of water removed per kg of air passing, and the volume of drying air required to remove 20 kg water per hour.

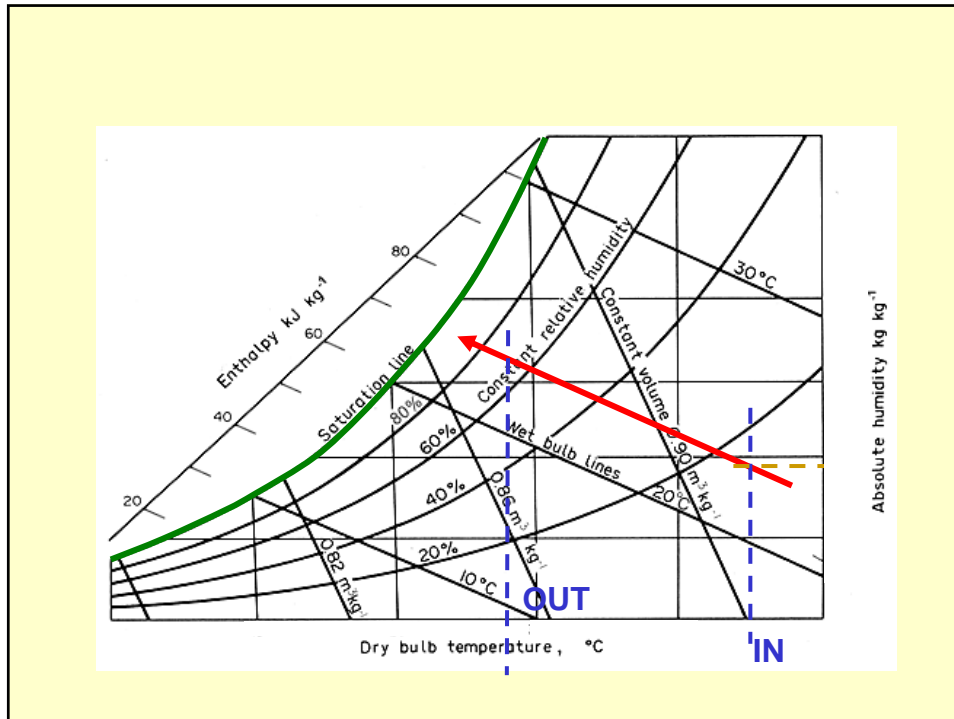
Using the psychrometric chart (high T version), the inlet air condition shows the humidity of the drying air to be 0.01 kg kg⁻¹ and its specific volume to be 0.96 m³ kg⁻¹. **Through the dryer, the condition of the air follows a constant wet-bulb line of about 27°C**, so at 35°C its condition is a humidity of 0.0207 kg kg⁻¹.

Water removed = (0.0207 - 0.010) = 0.0107 kg kg⁻¹ of air.

So each kg, i.e. 0.96 m³, of air passing will remove 0.0107 kg water,

Volume of air to remove 20 kg h⁻¹ = (20/0.0107) x 0.96 = 1794 m³ h⁻¹

If air is cooled, then initially its condition moves along a line of constant humidity, horizontally on a psychrometric chart, until it reaches the saturation curve at its dew point. Further cooling then proceeds down the saturation line to the final temperature, with water condensing to adjust the humidity as the saturation humidity cannot be exceeded.



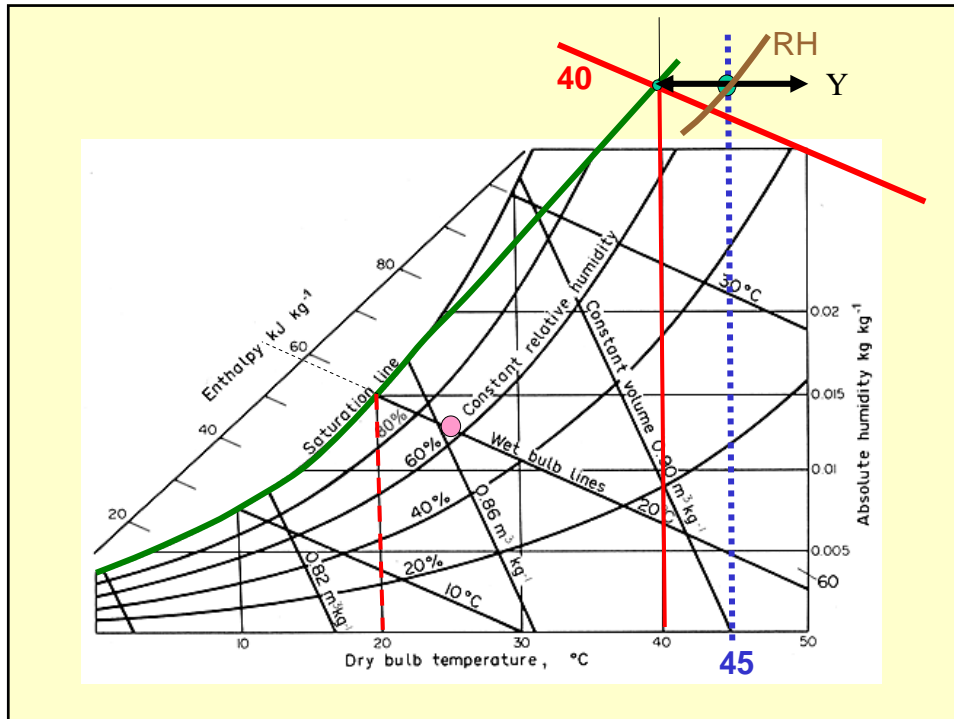
EXAMPLE. Relative humidity of air leaving a dryer

The air emerging from a dryer, with an exit temperature of 45°C, passes over a surface which is gradually cooled. It is found that the first traces of moisture appear on this surface when it is at 40°C. Estimate the relative humidity of the air leaving the dryer.

On the psychrometric chart, the saturation temperature is 40°C and proceeding at constant humidity from this, the 45°C line is intersected at a point indicating:

relative humidity = 76%

In dryers, it is **sometimes useful to reheat the air so as to reduce its relative humidity and thus to give it an additional capacity to evaporate more water from the material** being dried. This process can easily be followed on a psychrometric chart.



EXAMPLE. Reheating of air in a dryer

A flow of $1800 \text{ m}^3 \text{ h}^{-1}$ of air initially at a temperature of 18°C and 50% RH is to be used in an air dryer. It is heated to 140°C and passed over a set of trays in a shelf dryer, which it leaves at 60% RH. It is then reheated to 140°C and passed over another set of trays which it leaves at 60% RH again. Estimate the energy necessary to heat the air and the quantity of water removed per hour.

From the psychrometric chart the humidity of the initial air is $0.0062 \text{ kg kg}^{-1}$, specific volume is $0.834 \text{ m}^3 \text{ kg}^{-1}$, and enthalpy 35 kJ kg^{-1} .

Proceeding at constant humidity to a temperature of 140°C , the enthalpy is found (high temperature chart) to be 160 kJ kg^{-1} .

Proceeding along a wet-bulb line to an RH of 60% gives the corresponding temperature as 48°C and humidity as 0.045 kg kg^{-1} .

Reheating to 140°C keeps humidity constant and enthalpy goes to 268 kJ kg^{-1} .

Hence along a wet-bulb line to 60% RH gives humidity of 0.082 kg kg^{-1} .

Total energy supplied = ΔH in heating and reheating
= $268 - 35 = 233 \text{ kJ kg}^{-1}$

Total water removed = ΔY
= $0.082 - 0.0062 = 0.0758 \text{ kg kg}^{-1}$

1800 m³ of air per hour = $1800/0.834$
= $2158 \text{ kg h}^{-1} = 0.6 \text{ kg s}^{-1}$

Energy taken in by air = $233 \times 0.6 \text{ kJ s}^{-1} = 140 \text{ kW}$

Water removed in dryer = 0.6×0.0758
= $0.045 \text{ kg s}^{-1} = 163 \text{ kg h}^{-1}$

Exit temperature of air (from chart) = 60°C.

Consideration of psychrometric charts, and what has been said about them, will show that they can be used for calculations focused on the air, for the purposes of air conditioning as well as for drying.

XAMPLE. Air conditioning

... in a tropical country, it is desired to provide processing air conditions of 15°C and 80% RH. The ambient air is at 31.5°C and 90% RH. If the chosen method is to cool the air to condense out enough water to reduce the water content of the air sufficiently, then to reheat if necessary, determine the temperature to which the air should be cooled, the quantity of water removed and the amount of reheating necessary. The processing room has a volume of 1650 m³ and it is estimated to require six air changes per hour.

Using the psychrometric chart:

Initial humidity is $0.0266 \text{ kg kg}^{-1}$.

Final humidity is $0.0085 \text{ kg kg}^{-1}$.

Saturation temperature for this humidity is 13°C.

Therefore the air should be cooled to 13°C

At the saturation temperature of 13°C, the enthalpy is 33.5 kJ kg^{-1}

X At the saturation temperature of 13°C, the enthalpy is 33.5 kJ kg⁻¹

At the final conditions, 15°C and 80 % RH, the enthalpy is 37 kJ kg⁻¹ and the specific volume of air is 0.827 m³ kg⁻¹.

Assuming that the air changes are calculated at the conditions in the working space.

$$\begin{aligned} \text{Mass of air to be conditioned} &= (1650 \times 6)/0.827 \\ &= 11,970 \text{ kg h}^{-1} \end{aligned}$$

$$\begin{aligned} \text{Water removed per kg of dry air } \Delta Y & \\ &= 0.0266 - 0.0085 = 0.018 \text{ kg kg}^{-1} \end{aligned}$$

$$\begin{aligned} \text{Mass of water removed per hour} & \\ &= 11,970 \times 0.018 = 215 \text{ kg h}^{-1} \end{aligned}$$

$$\text{Reheat required } \Delta H = (37 - 33.5) = 3.5 \text{ kJ kg}^{-1}$$

Total reheat power required

$$= 11,970 \times 3. = 11.6 \text{ kJ s}^{-1} = \underline{11.6 \text{ kW.}}$$

X

Measurement of Humidity

Methods depend largely upon the concepts that have been presented in the preceding sections, but because they are often needed it seems useful to set them out specifically. Instruments for the measurement of humidity are called **hygrometers**.

Wet- and dry-bulb thermometers. The dry-bulb temperature is the normal air temperature and the only caution that is needed is that if the thermometer bulb, or element, is exposed to a surface at a substantially higher or lower temperature the possibility of radiation errors should be considered. A simple method to greatly reduce any such error is to interpose a radiation shield, e.g. a metal tube, which stands off from the thermometer bulb 1 cm or so and prevents direct exposure to the radiation source or sink.

X

For the wet bulb thermometer, covering the bulb with a piece of wicking, such as a hollow cotton shoelace of the correct size, and dipping the other end of the wick into water so as to moisten the wet bulb by capillary water flow, is adequate. The necessary aspiration of air past this bulb can be effected by a small fan or by swinging bulb, wick, water bottle and all through the air, as in a sling psychrometer. The maximum difference between the two bulbs gives the wet-bulb depression and a psychrometric chart or appropriate tables will then give the relative humidity.

X **dew-point meters.** These measure the saturation or dew-point temperature by cooling a sample of air until condensation occurs. The psychrometric chart or a scale on the instrument is then used to give the humidity. For example, a sample of air at 20°C is found to produce the first signs of condensation on a mirror when the mirror is cooled to 14°C. The chart shows by moving horizontally across, from the saturation temperature of 14°C to the constant temperature line at 20°C, that the air must have a relative humidity of 69%.

The hair hygrometer. Hairs expand and contract in length according to the relative humidity. Instruments are made which give accurately the length of the hair and so they can be calibrated in humidities.

X

Electrical resistance hygrometers. Some materials vary in their surface electrical resistance according to the relative humidity of the surrounding air. Examples are aluminium oxide, phenol formaldehyde polymers, and styrene polymers. Calibration allows resistance measurements to be interpreted as humidity.

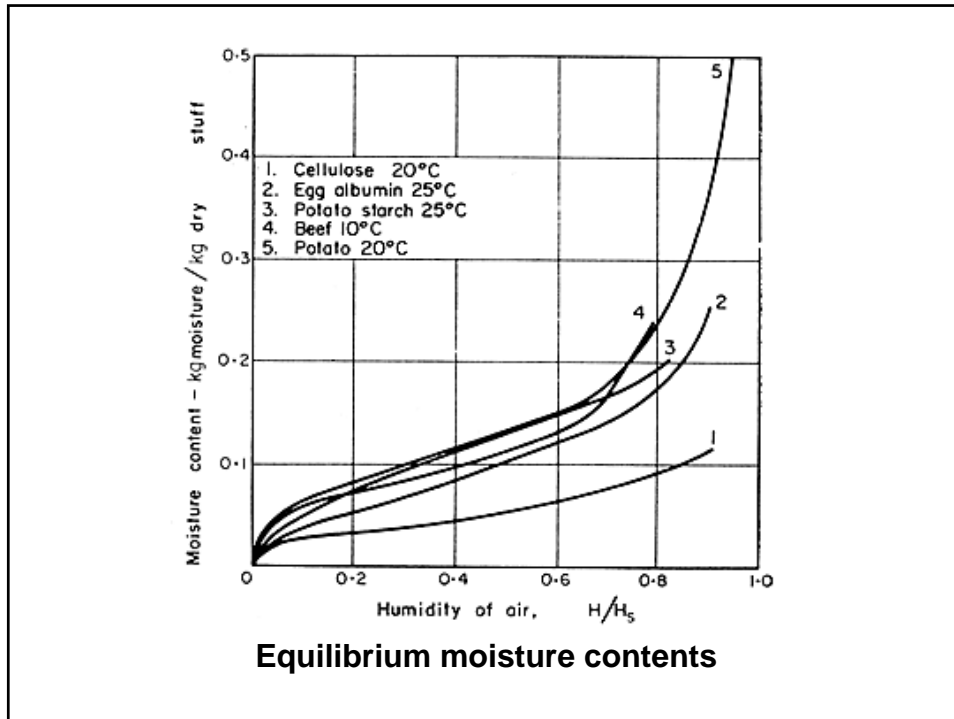
Lithium chloride hygrometers. In these a solution of lithium chloride is brought to a temperature such that its partial pressure equals the partial pressure of water vapor in the air. The known vapor pressure-temperature relationships for lithium chloride can then be used to determine the humidity of the air.

EQUILIBRIUM MOISTURE CONTENT

The equilibrium vapor pressure above a material is a function of (1)T, (2) water content of the material, (3) by the way in which the water is bound in the material, and (4) by the presence of any constituents soluble in water.

Under a given vapor pressure of water in the surrounding air, a paper attains a moisture content **in equilibrium** with its surroundings when there is no exchange of water between the paper and its surroundings. This is called its **equilibrium moisture content**.

NEXT: Plot the equilibrium vapor pressure against moisture content **or** the relative humidity of the air in equilibrium with the paper against moisture content of the paper.



AIR DRYING

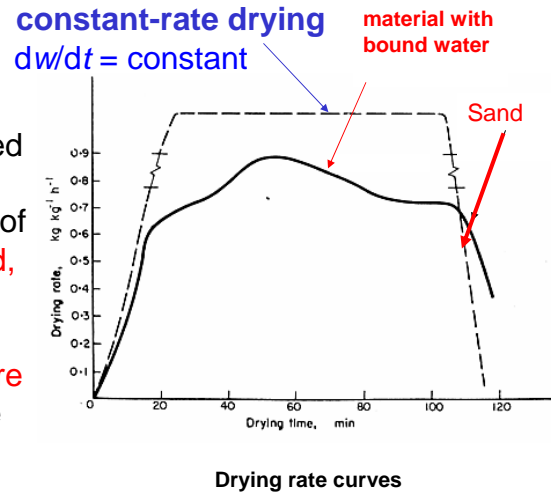
The rate of removal of water depends on (1) the conditions of the air, (2) the properties of the material (paper/pulp) and the (3) design of the dryer.

Moisture can be held in varying degrees of bonding. Formerly, it was considered that water in a fibrous materials came into one or other of two categories, **free water** or **bound water**.

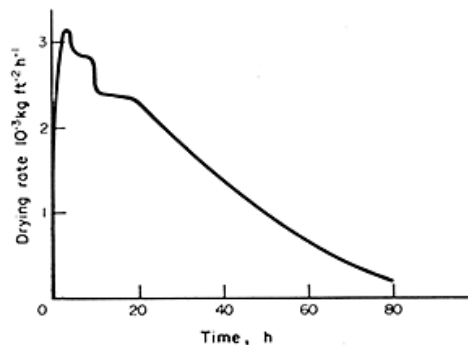
Water is held by forces whose intensity ranges from the (1) **very weak forces** retaining surface moisture to (2) **very strong chemical bonds**.

In drying, it is expected that the water that is loosely held will be removed most easily. Thus it would be expected that drying **rates would decrease as moisture content decreases**, with the remaining water being bound more and more strongly as its quantity decreases.

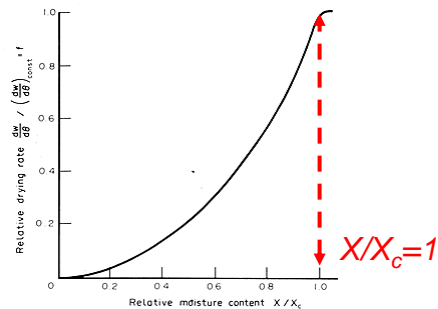
In many cases, a substantial part of the water is found to be **loosely bound**. This water can, for drying purposes, be considered as **free water** at the surface. A comparison of the drying rates of **sand**, a material with mostly **free water**, with a material containing **more bound water** shows the effect of the binding of water on drying rates.



In paper, unlike impervious materials such as sand, **after a period of drying at a constant rate** it is found that the **water then comes off more slowly**.



Curve plotting the rate of drying as a percentage of the constant (critical) rate, against moisture content:



The change from constant drying rate to a slower rate occurs at different moisture contents for different materials.

The moisture content at which this change of rate occurs is known as the **critical moisture content, X_c** .

Many materials do **not** show a true constant rate drying period. They do, however, often show quite a sharp break after a slowly and steadily declining drying rate period and the concept of constant rate is still a useful approximation.

The end of the constant rate period, **when $X = X_c$** at the break point of drying-rate curves, signifies that the **water has ceased to behave as if it were at a free surface and that factors other than vapor-pressure differences are influencing the rate of drying.**

Thereafter the drying rate decreases and this is called the **falling-rate period of drying.**

1. depends upon diffusion through the material
2. the changing energy-binding pattern of the water molecules
3. experimental drying curves are the only adequate guide to design.

Calculation of Constant Drying Rates

In the constant-rate period, the water is **being evaporated from what is effectively a free water surface**. The rate of **removal of water can then be related to the rate of heat transfer**, if there is no change in the temperature of the material and therefore **all heat energy transferred to it must result in evaporation of water**. The **rate of removal of the water is also the rate of mass transfer**, from the solid to the ambient air. These two - mass and heat transfer - must predict the same rate of drying for a given set of circumstances.

Mass transfer: the driving force is the **difference of the partial water vapor pressure between the material and the air**. The extent of this difference can be obtained, knowing the temperatures and the conditions, by reference to tables or the psychrometric chart. *Alternatively*, the driving force may be expressed in terms of **humidity driving forces** and the numerical values of the **mass-transfer coefficients in this case are linked to the others through the partial pressure/humidity relationships**.

EXAMPLE 7.13. Rate of evaporation on drying

The **mass-transfer coefficient** from a free water surface to an adjacent moving air stream has been found to be **0.015 kgm⁻² s⁻¹**. Estimate the rate of evaporation from a **surface of 1 m² at a temperature of 28°C** into an air stream with a dry-bulb temperature of 40°C and RH of 40% and the consequent necessary rate of supply of heat energy to effect this evaporation.

The **humidity of saturated air at 40°C** is 0.0495 kg kg⁻¹.

Humidity of air at 40°C and 40%RH = 0.0495 x 0.4 = 0.0198 kg kg⁻¹ = Y_a

The humidity of **saturated air at 28°C** is 0.0244 kg kg⁻¹ = Y_s

$$\text{Driving force} = (Y_s - Y_a) = (0.0244 - 0.0198) \text{ kg kg}^{-1}$$

$$= 0.0046 \text{ kg kg}^{-1}$$

$$\text{Rate of evaporation} = k'_g A (Y_s - Y_a) = 0.015 \times 1 \times 0.0046 = 6.9 \times 10^{-5} \text{ kg s}^{-1}$$

$$\text{Latent heat of evaporation of water at } 28^\circ\text{C} = 2.44 \times 10^3 \text{ kJ kg}^{-1}$$

$$\text{Heat energy supply rate per square meter} = 6.9 \times 10^{-5} \times 2.44 \times 10^3 \text{ kJ s}^{-1}$$

$$= 0.168 \text{ kJ s}^{-1} = \underline{0.168 \text{ kW}}.$$

The problem in applying such apparently simple relationships to provide the essential rate information for drying, is in the prediction of the mass transfer coefficients. In the section on heat transfer, methods and correlations were given for the prediction of heat transfer coefficients. Such can be applied to the drying situation and the heat transfer rates used to estimate rates of moisture removal. The reverse can also be applied.

EXAMPLE. Heat transfer in air drying

Using the data from the previous example, estimate the heat transfer coefficient needed from the air stream to the water surface.

$$\text{Heat-flow rate} = q = 168 \text{ J s}^{-1} \text{ from Example}$$

Temperature difference = dry-bulb temperature of air - wet-bulb temperature (at solid surface)

$$= (40 - 28) = 12^\circ\text{C} = (T_a - T_s)$$

$$\text{Since } q = h_c A (T_a - T_s) \quad 168 = h_c \times 1 \times 12$$

$$h_c = \underline{14 \text{ J m}^{-2} \text{ s}^{-1} \text{ }^\circ\text{C}^{-1}}$$

Mass balances are also applicable, and can be used, in drying and related calculations.

EXAMPLE. Temperature and RH in air drying

In a low-temperature drying situation, air at 60°C and 10 % RH is being passed over a bed of diced material at the rate of 20 kg dry air per second. If the **rate of evaporation of water from the material, measured by the rate of change of weight of the material, is 0.16 kg s⁻¹** estimate the temperature and RH of the air leaving the dryer.

From the psychrometric chart

Humidity of air at 60°C and 10%RH

$$= 0.013 \text{ kg kg}^{-1}.$$

Humidity added to air in drying

$$= 0.16 \text{ kg}/20 \text{ kg dry air}$$

$$= 0.008 \text{ kg kg}^{-1}$$

Humidity of air leaving dryer

$$= 0.013 + 0.008$$

$$= 0.021 \text{ kg kg}^{-1}$$

Following on the psychrometric chart the wet-bulb line from the entry point at 60°C and 10%RH up to the intersection of that line with a constant humidity line of 0.021 kg kg⁻¹, the resulting **temperature is 41°C and the RH 42%**.

The heat-transfer rates can be used to estimate drying rates, through the Lewis ratio.

Remembering that $(Le) = (h_c/c_s k'_g) = 1$ for the air/water system (for air of the humidity encountered in ordinary practice $c_s \approx c_p \approx 1.02 \text{ kJ kg}^{-1} \text{ }^\circ\text{C}^{-1}$),

If h_c is in $\text{J m}^{-2} \text{ s}^{-1} \text{ }^\circ\text{C}^{-1}$, and k'_g in $\text{kg m}^{-2} \text{ s}^{-1}$

$k'_g = h_c/1000$, the values of h_c can be predicted using the standard relationships for heat-transfer coefficients.

EXAMPLE. Lewis relationship in air drying

In a previous example a value for k'_g of $0.0150 \text{ kg m}^{-2} \text{ s}^{-1}$ was used. It was also found that the corresponding heat-transfer coefficient for this situation was $15 \text{ J m}^{-2} \text{ s}^{-1} \text{ }^\circ\text{C}^{-1}$ as calculated in the following one. Does this agree with the expected value from the Lewis relationship for the air/water system?

$$\begin{aligned}h_c &= 15 \text{ J m}^{-2} \text{ s}^{-1} \text{ }^\circ\text{C}^{-1} \\ &= 1000 \times 0.0150 \\ &= \underline{1000 \times k'_g \text{ as the Lewis relationship predicts.}}\end{aligned}$$

Falling rate Drying

The highest rate of drying is normally the constant rate situation, then as drying proceeds the moisture content falls and the access of water from the interior of the material to the surface affects the rate and decreases it. The situation then is complex with moisture gradients controlling the observed drying rates.

Calculation of Drying Times

Drying rates, determined experimentally or predicted

Calculate drying times

Drying equipment and operations can be designed.

Complication: the drying rates vary throughout the dryer with time as drying proceeds, and with the changing moisture content of the material.

One simplification is to assume that the **temperature and RH of the drying air are constant.**

For the constant-rate period, the time needed to remove the quantity of water which will reduce the material to the critical moisture content X_c can be calculated by dividing the evaporated water $w(\Delta X)$ by the drying rate.

dry mass of material

$$\text{So } t = w(X_o - X_c) / (dw/dt)_{\text{const}}$$

$$(dw/dt)_{\text{const}} = k'_g A(Y_s - Y_a)$$

X_o = initial moisture content

X_c = final moisture content (critical moisture content on a dry basis)

w is the amount of dry material in the material

$(dw/dt)_{\text{const}}$ = constant-drying rate

IF the **drying rate is reduced by a factor f** then this can be incorporated to give:

$$\Delta t = w(\Delta X) / f(dw/dt)_{\text{const}}$$

and this has to be integrated down to $X = X_{\text{final}}$

f expresses the ratio of the actual drying rate to the maximum drying rate corresponding to the free surface-moisture situation.

EXAMPLE. Time for air drying at constant rate

100 kg of a material are dried from an **initial water content of 80%** on a wet basis and with a surface area of 12 m². Estimate the time needed to dry to 50% moisture content on a wet basis, assuming constant-rate drying in air at a temperature of 120°C dry bulb and 50°C wet bulb. Under the conditions in the dryer, measurements indicate the **heat-transfer coefficient to the solid surface from the air to be 18 J m⁻² s⁻¹ °C⁻¹**.

From the data $X_o = 0.8/(1 - 0.8) = 4 \text{ kg kg}^{-1}$ ----- note dry basis

$X_{\text{final}} = 0.5/(1 - 0.5) = 1 \text{ kg kg}^{-1}$,

and from the psychrometric chart, $Y_s = 0.087$ and $Y_a = 0.054 \text{ kg kg}^{-1}$

From the Lewis relationship $K'_g = 18 \text{ g m}^{-2} \text{ s}^{-1} = 0.018 \text{ kg m}^{-2}$

$w = 100(1 - 0.8) = 20 \text{ kg (dry mass)}$ and $w (X_o - X_{\text{final}}) =$ water evaporated

Now we have $(dw/dt)_{\text{const}} = K'_g A (Y_s - Y_a)$

$$t = w (X_o - X_f) / [K'_g A (Y_s - Y_a)] = 20(4 - 1) / [0.018 \times 12 \times (0.087 - 0.054)] =$$

$60 / 7.128 \times 10^{-3} = 8417 \text{ s} = 2.3 \text{ h}$ (to remove 60 kg of water).

During the falling-rate period, the procedure outlined above can be extended, **using the drying curve for the particular material** and the conditions of the dryer.

Sufficiently **small differential quantities of moisture content to be removed have to be chosen**, over which the drying rate is effectively constant, so as to give an accurate value of the total time. As the moisture content above the equilibrium level decreases so the drying rates decrease, and drying times become long.

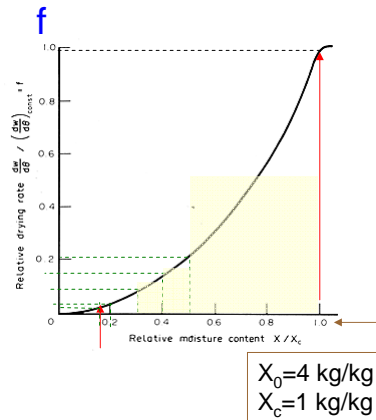
EXAMPLE . Time for drying during falling rate

Continuing previous example, for the particular material material, the critical moisture content, $X_c = 100\%$ and the equilibrium moisture content under the conditions in the dryer is 15%. Estimate the total time to dry down to 17%, all moisture contents being on a dry basis.

$$\Delta t = w(\Delta X) / [f(dw/dt)_{const}]$$

can be applied, over small intervals of moisture content and multiplying the constant rate by the appropriate reduction factor (f) read off from the figure. This can be set out in a table.

Note the temperature and humidity of the air are assumed to be constant throughout the drying.



X	0.5	0.4	0.3	0.2	0.18	0.17
$w(X_1 - X_2)$	2	2	2	0.4	0.2	
f	0.86	0.57	0.29	0.11	0.005	
$1/f(dw/dt)_{const}$ $= 1 / f(7.128 \times 10^{-3})$	1.63×10^2	2.46×10^2	4.84×10^2	1.28×10^3	2.81×10^4	
$t \rightarrow \Delta t = w(\Delta X) / [f(dw/dt)_{const}]$	326	492	968	512	5620	

$\Sigma t = 7918 \text{ s} = 2.2 \text{ h}$ (to remove 6.6 kg of water) = time at falling rate

Therefore total drying time = (2.3 + 2.2) h = 4.5 h.

The example shows how as the moisture level descends toward the equilibrium value so the **drying rate becomes slower and slower**.

Humidity or partial pressure driving force is tending to zero as the equilibrium moisture content is approached.

The surface temperature rises above the wet-bulb temperature once the surface ceases to behave as a wet surface. **The surface temperature then climbs towards the dry-bulb temperature of the air** as the moisture level continues to fall, thus leading to a continuously **diminishing temperature driving force** for surface heat transfer.

This calculation procedure can be applied to more **complicated dryers**, considering them **divided into sections**, and applying the drying rate equations and the input and output conditions to these sections sequentially to build up the whole situation in the dryer.

CONDUCTION DRYING

So far the dryingby hot air.

Drying by contact with a hot surface:

A continuous version of this is the drum or roller dryer where the material is coated as a thin layer over the surface of a revolving heated horizontal cylinder. In such a case, the material dries for as much of one revolution of the cylinder as is mechanically feasible.

The amount of drying is substantially controlled by the rate of heat transfer and estimates of the heat transfer rate can be used for calculations of the extent of drying.

EXAMPLE. Moisture content of starch after drum drying

A drum dryer is being used to dry a starch-based paste. The initial moisture content of the starch is 75% on a wet basis, the drum surface temperature is 138°C and the starch layer outer surface 100°C. The estimated heat transfer coefficient from the drum surface to the drying starch is $800 \text{ J m}^{-2} \text{ s}^{-1} \text{ }^\circ\text{C}^{-1}$.

Assume that the thickness of the starch on the drum is 0.3 mm and the thermal conductivity of the starch is $0.55 \text{ J m}^{-1} \text{ s}^{-1} \text{ }^\circ\text{C}^{-1}$. If the drum, 1 m diameter and 1 m in length, is rotating at 2 rev/min and the starch occupies 3/4 of the circumference, estimate the moisture content of the film being scraped off.

Assume the critical moisture content for the starch material is 14% on a dry basis, and that conduction heat transfer is through the whole film thickness to give a conservative estimate.

Initial moisture content = 75 % wet basis
= $0.75/(1 - 0.75) = 3 \text{ kg kg}^{-1}$ **dry basis.**

Total quantity of material on drum = $(\pi \times D \times \frac{3}{4}) \times 1 \times 0.0003 \text{ m}^3$
= $7.1 \times 10^{-4} \text{ m}^3$.

Assuming a density of the starch paste of 1000 kg m^{-3} ,
Weight on drum = $7.1 \times 10^{-4} \times 10^3 = \underline{0.71 \text{ kg (wet mass)}}$

$$1/U = 1/800 + 0.0003/0.55 = 1.25 \times 10^{-3} + 0.55 \times 10^{-3}$$
$$= 1.8 \times 10^{-3}$$

$$U = 556 \text{ Jm}^{-2} \text{ s}^{-1} \text{ } ^\circ\text{C}^{-1}$$

$$q = UA \Delta T = 556 \times \pi \times D \times 1 \times 0.75 \times (138 - 100) = 49.8 \text{ kJs}^{-1}$$

Latent heat of evaporation of water = 2257 kJ kg^{-1}

Rate of evaporation = $q/\lambda = 0.022 \text{ kg s}^{-1}$.

Residence time of starch on drum: at 2 rev min

1 rev takes 30s, but the material is on for $\frac{3}{4}$ rev.

$$\text{Residence time} = (\frac{3}{4}) \times 30 = 22.5 \text{ sec}$$

$$\text{Water removed} = 22.5 \text{ s} \times 0.022 \text{ kg/s} = \underline{0.495 \text{ kg}}$$

$$\text{Initial quantity of water} = 0.71 \times 0.75 = 0.53 \text{ kg.}$$

$$\text{Dry solids} = 0.71 \times 0.25 = 0.18 \text{ kg.}$$

$$\text{Residual water} = (0.53 - 0.495) = 0.035 \text{ kg.}$$

Water content (wet basis) remaining

$$= 0.035 / (0.18 + 0.035) = \underline{16\%}$$