Unit 2: Psychrometrics

Unit objectives

On completion of this unit you should be able to:

- Understand the main components of the psychrometric chart
- Interpret the main psychrometric processes
- Represent the processes on the chart
- Make use of the room ratio line

Unit topics

- The psychrometric chart
- Air & water vapour mixtures
- Psychrometric processes used in air conditioning

Suggested reading

- Jones W P, *Air Conditioning Engineering,* 4th Edition, Edward Arnold, 1994. Chapters 4 & 5.
- Legg R, *Air Conditioning Systems,* Batsford, 1991. Chapter 1 & 2.
- Eastop T D & Watson W E, *Mechanical Services for Buildings,* Longmans, 1992. Chapter 1.

2.1 Introduction

Psychrometrics studies those thermodynamic properties of the air that are relevant to thermal comfort design and loads, both sensible and latent, calculation. The thermodynamic properties of dry air and saturated water vapour are well established and therefore the air throughout the building, both outdoor, and indoor, or in the air conditioning ductworks, is considered a mixture of the two, and its properties can be derived from those of the two fluids.

This unit defines all the major psychrometric properties of the air. The end of the units discusses how the changes in these properties can be achieved using air conditioning measures.

2.2 Psychrometric data and chart

There are seven psychrometric variables that are concerned in building thermal calculation and thermal comfort design:

Dry bulb temperature	^{0}Cdb
Moisture content	kg/kg dry air
Wet bulb temperature	^{0}Cwb
Specific volume	m^3/kg
Percentage saturation	%
Specific enthalpy	kJ/kg

Only two of them are independent, which means that there are well defined relationships between these seven variables: any two of them can derive the other five variables. As the dry bulb temperature and moisture content can be measured relatively easier than others, they are used to as two basic variables for a Cartesian coordinate, which forms the base of CIBSE psychrometric chart that has been widely used in HVAC engineering.

A psychrometric chart (Fig 2.1) is a graph when under a given pressure, often the atmospheric pressure at the sea level, contours of the wet bulb temperature, specific heat, specific volume, percentage saturation, specific enthalpy are plotted on the Cartesian coordinate with the dry bulb temperature as its horizontal axis and the moisture content, vertical axis.

Therefore any point on the chart defines the thermodynamic properties of a mixture of the dry air and water vapour and therefore represents a specific state of the moist air.

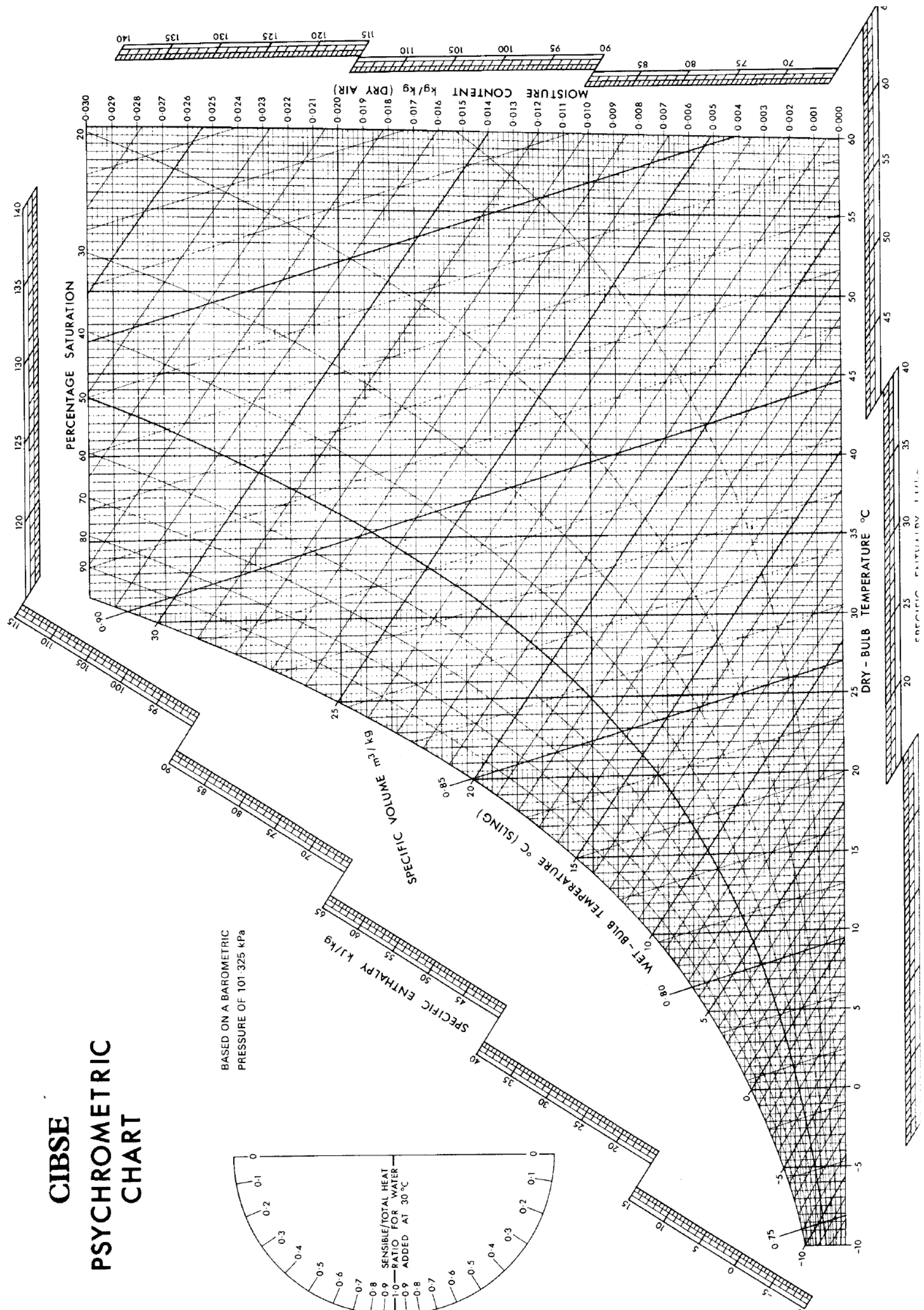

Fig 2.1 CIBSE Psychrometric chart on sea level

Moving from one point to another on the chart defines a specific psychrometric process that is achieved by a system. The value changes associated with the process assists the calculations in system design, such as loads estimation and condensation assessment. Therefore a psychrometric chart has often been used as a tool in HVAC designs. Section 2.3 presents details of some psychrometric processes that are commonly seen in HVAC engineering.

It is useful to define the following quantities and processes:

2.2.1 Dry-bulb Temperature (DBT)

This variable is a measure that shows the level of the internal energy of a given air. A similar variable is the height of an object indicates its potential energy. DBT can be easily measured by an ordinary thermometer, in Celsius (in Fahrenheit US and some other countries) or in Kelvin. It is the horizontal axis of the psychrometric chart.

2.2.2 Moisture Content

Also called humidity ratio, or mixing ratio or specific humidity, is the proportion of mass of water vapour per unit mass of dry air at the given conditions. Its unit is kg/kg dry air. It is the vertical axis of the psychrometric chart.

2.2.3 Wet-bulb Temperature (WBT)

This variable is defined as the temperature of the sample air having passed over a large surface of water through a constant pressure, idea, and adiabatic saturation process. In practice, it is measured by an ordinary thermometer whose sensor, its tip bulb is wrapped with a wet sock that is saturated with water that are in the same temperature of the air and evaporating moisture into the passing by air. On the chart its contours are a group of parallel slope lines. Its unit is the same as the DBT, Celsius.

2.2.4 Dew point temperature

Dew point temperature is the temperature at which saturated air has the same vapour pressure as the sample.

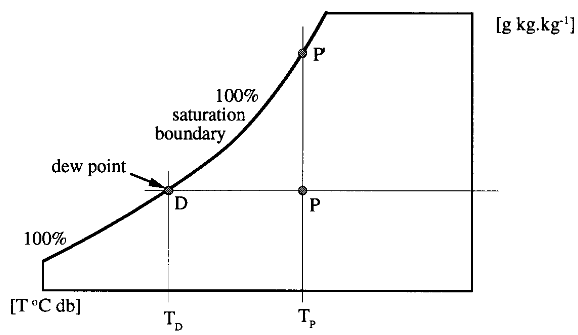

Fig 2.2 State points on the psychrometric chart

It is also the temperature at which moisture condenses out of a particular air stream. Point D above plotted against dry bulb temperature forms the 100% saturation line or left hand boundary of a psychrometric chart.

2.2.5 Relative humidity (or rh)

% rh may be defined as the ratio of vapour pressure at P above at temperature T_p to the vapour pressure at saturation at temperature T_p i.e. point p' above.

2.2.6 Percentage saturation or humidity ratio

This is the ratio of moisture content at P with temperature T_p to the saturation moisture content at p' with temperature T_p. For all practical purposes this is the same as rh.

2.2.7 Humid or specific volume

This is the volume occupied by the moist air, or air-water vapour moisture at a particular temperature and pressure.

2.2.8 Humid specific heat

This is the effective specific heat of an air-water vapour mixture and is calculated from an addition.

$$CH_{UMID} = C_{AIR} M_{AIR} + C_{WATER} M_{WATER} \tag{2.1}$$

Where,
M_{AIR} the mass weight of the dry air;
C_{AIR} the specific heat of the dry air;
M_{WATER} the mass weight of the water vapour;
C_{WATER} the specific heat of the water vapour;

If $Mass_{AIR} = 1$kg and $Mass_{WATER} = g$ kg/kg

then

$$CH_{UMID} = (C_{AIR} + g\, C_{WATER}) \text{ kg/kg dry air} \tag{2.2}$$

In most conditions, these two common fluids have the specific heat of:

$C_{AIR} = 1.01$ kJ/kg, $C_{WATER} = 1.89$ kJ/kg

Therefore the specific heat of the moist air is:

$$CH_{UMID} = (1.01 + 1.89g) \text{ kJ/kg dry air} \tag{2.3}$$

2.2.6 Specific enthalpy (*h*)

Also called heat content per unit mass, the specific enthalpy is the sum of the internal heat (energy) of the moist air, including both of the air and water vapour, at the temperature "t" that is above the reference temperature " t_{DATUM}" which in practice often taken as 0 ˚C.

$$h = M_{AIR}\ C_{AIR}\,(t - t_{DATUM}) + M_{WATER}\, C_{WATER}\,(t - t_{DATUM}) + M_{WATER}\ L_{WATER}$$

Where

M_{AIR} the mass weight of the dry air;
C_{AIR} the specific heat of the dry air;
M_{WATER} the mass weight of the water vapour;
C_{WATER} the specific heat of the water vapour;
L_{WATER}, the latent heat of evaporation water

if $M_{AIR} = 1$ kg, $M_{WATER} = g$ kg/kg dry air; $T_{DATUM} = 0$ °C and the latent heat of evaporation = 2500kJ/kg

then at a temperature "t" the specific enthalpy of the moist air is

$$h = t(1.01 + 1.89g) + 2500g. \tag{2.4}$$

2.3 Psychrometric processes

2.3.1 Mixture state

Mixing two flows of moist air, of which the states, "O" and "R" are plotted on a chart (Fig 2.3), produces a new state for the mixture.

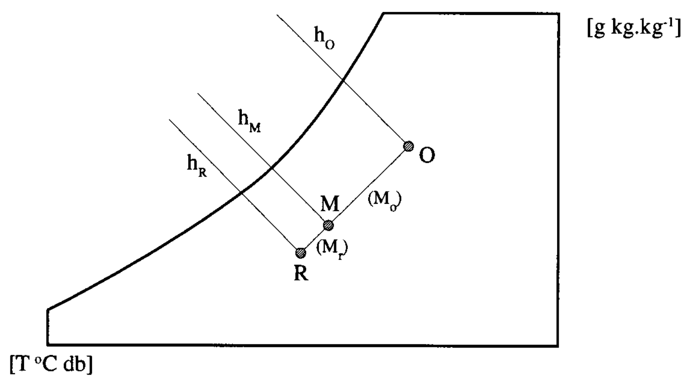

Fig 2.3 Mixture state

The mixture state point lies on the straight line **OR** so that

$$\frac{\mathrm{OM}}{\mathrm{MR}} = \frac{m_r}{m_O} \tag{2.5}$$

Where m_r and m_o are the mass flow rates of the two moist air components at states R and O respectively. OM, RM may be expressed as Δh, Δg or ΔT.
More practically, the state of the mixture can be calculated easily using mass flow rates of the two components:

$$T_M = \frac{m_o}{m_o + m_R} T_o + \frac{m_R}{m_o + m_R} T_R; \tag{2.6}$$

$$g_M = \frac{m_o}{m_o + m_R} g_o + \frac{m_R}{m_o + m_R} g_R \text{ and} \tag{2.7}$$

$$h_M = \frac{m_o}{m_o + m_R} h_o + \frac{m_R}{m_o + m_R} h_R \tag{2.8}$$

2.3.2 Sensible heating or cooling

This is a process involving a change of state of a moist air volume at constant moisture content, represented by a horizontal line on a psychrometric chart. This process in reality is achieved normally by letting air, with temperature T_A, go through a heat exchanger, of which surface temperature is T_C.

$T_C > T_A$ represents sensible heating whilst $T_C < T_A$, sensible cooling (Fig 2.4). The temperature after passing the heat exchanger will be often between T_C and T_A. This is because that only a portion of the air comes into contact with the surface of the heat exchanger, and therefore as the mean temperature of the whole flow, T_B will surely unable to be the exact temperature of the surface, T_C. The more the portion comes into the contact with the exchanger, the closer the T_B is to T_C.

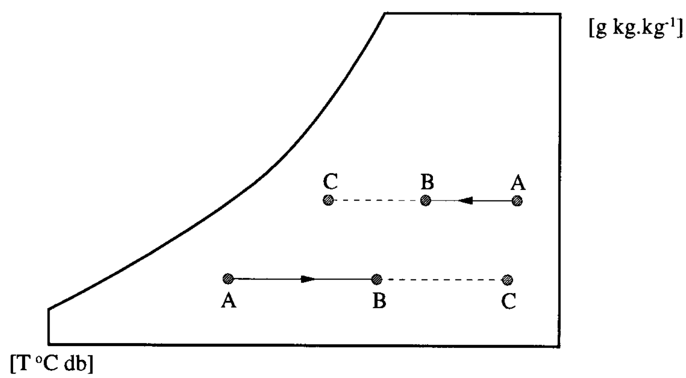

Fig 2.4 Sensible cooling and heating

Therefore a new variable is introduced to quantify such level of contact:

$$\text{Contact factor} = \frac{\text{temperature change of the flow}}{\text{temperature difference between the surface and the incoming flow}}$$

For heating: $f_c = \dfrac{(T_B - T_A)}{(T_C - T_A)}$ and (2.9)

the heat supplied by the primary medium will be $q = mc(T_B - T_A) = m(h_B - h_A)$

whilst for cooling: $f_c = \dfrac{(T_A - T_B)}{(T_A - T_C)}$ and (2.10)

the heat supplied by the primary medium will be $q = mc(T_A - T_B) = m(h_A - h_B)$

Sensible heating or cooling occurs at constant moisture content.

2.3.3 Latent heating or cooling

This is a process involving a change of state of a moist air volume at constant dry bulb temperature. Represented by a vertical line on a psychrometric chart.

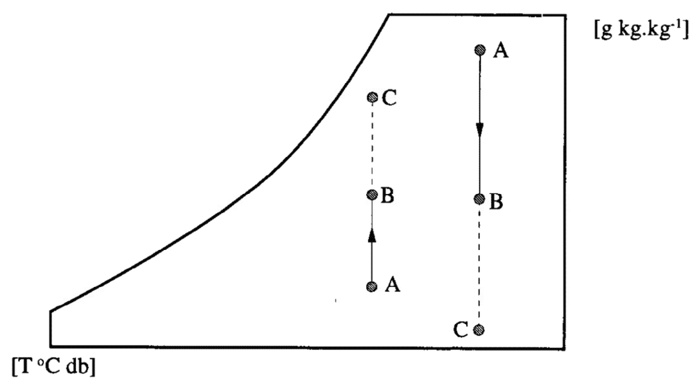

Fig 2.5 Latent cooling and heating

2.3.4 Dehumidification by cooling coil or air washer

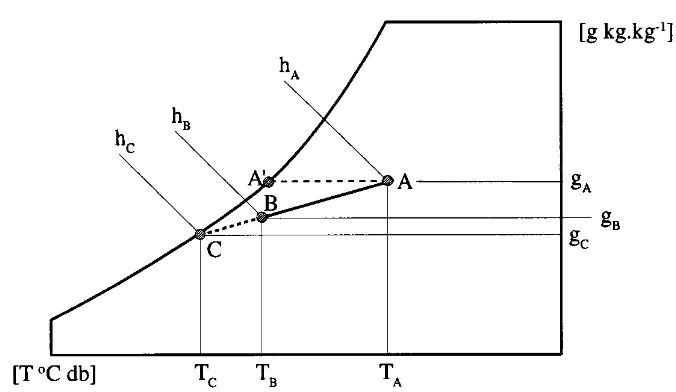

Fig 2.6 Dehumidification by cooling

If the surface temperature of the heat exchanger, such as the cooling coil, or the spray water temperature Tc, is less than the moist air dew point temperature, A", then dehumidification and cooling occurs.

The efficiency of the process is measured by the apparatus contact factor AB/AC where AB, Ac can be measured in Δh, ΔT or Δg. The design of the coil or heat exchanger and arrangement of the air passing over the coils determine largely the contact factor. A high contact factor is normally desirable in HVAC engineering.

Cooling load $q = mc(T_B - T_A) = m(h_B - h_A)$, this heat to be absorbed by primary medium in cooler or spray water.

2.3.4 Humidification with heating

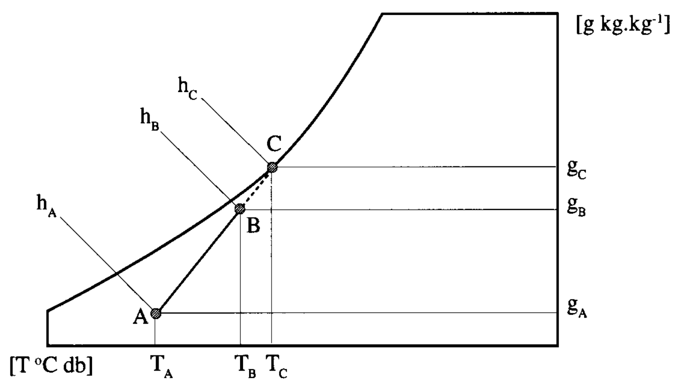

Fig 2.7 Humidification with heating

If spray water at a temperature T_C > air dry bulb temperature T_A is used then humidification with heating occurs.

Heating load $q = m(h_B - h_A)$. (2.11)

Humidifying efficiency is given by AB/AC where AB, AC may be measured in Δh, Δg or ΔT. T_C is the apparatus dew point temperature.

2.3.6 Humidification with cooling

As moist air passes through a spray chamber some evaporation of the spray droplets occurs increasing the air moisture content. Another typical application of this process is the wind passing over a water fountain spray.

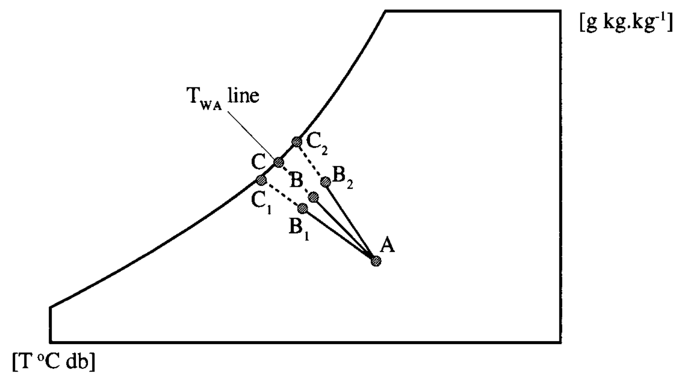

Fig 2.8 Humidification with cooling

If the spray water temperature $T_C = T_{WA}$ the air wet bulb temperature then the process is adiabatic and occurs along a constant wet bulb temperature line.

Humidifying efficiency = $\frac{AB}{AC}$ or $\frac{AB_1}{AC_1}$ etc.

2.3.7 Humidification by water injection

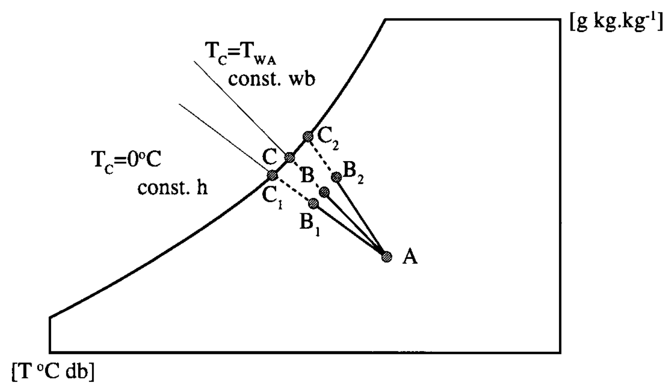

Fig 2.9 Humidification by water injection

Final state point B can never reach the saturation line if all water injected in evaporated. If T_C, the water temperature, is zero then the process occurs along a constant enthalpy line.

If T_C = air wet bulb temperature the process occurs along constant wet bulb temperature line.

If T_C is above air wet bulb temperature then the process occurs along a line joining A to C_2 on the saturation curve.

For most practical purposes though, a line of constant wet bulb temperature can represent water injection.

Mass balance gives $g_A + m_W = g_B$. (2.12)

Energy balance gives $h_A + h_W = h_B$ (2.13)

2.3.8 Humidification by steam injection

Steam is increasingly being used for humidification. The enthalpy of the steam has very little effect on the process line on the chart. Practically, a line of constant dry bulb temperature represents steam injection.

As with water injection, steam injection can be considered using a mass and energy balance.

$$g_B = g_A + m_S$$

$$h_B = h_A + h_S$$

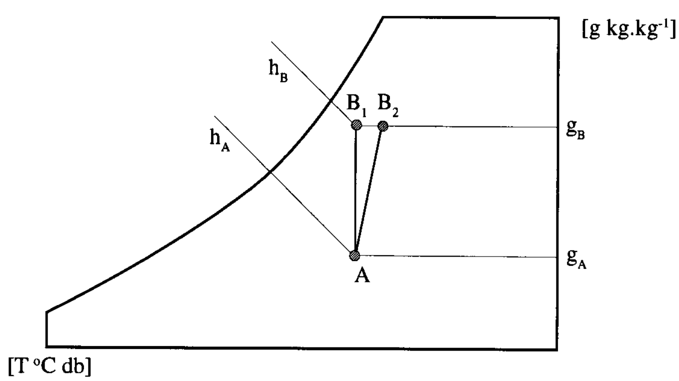

Fig 2.10 Humidification by steam injection

2.4 Sensible and latent heat loads

Conditioned air supplied to a room via an air conditioning system has to maintain the room conditions within the design limits. Normally the desired conditions will be specified in terms of dry bulb temperature and moisture content or relative humidity.

A room with no air conditioning will respond to outside conditions, due to heat transfer either to or from the enclosure, and to internal conditions, such as heat producing equipment or, more importantly, the evaporation of extra moisture into the air either due to a process or human occupation.

The response of the measured conditions in the room can be split into two "heat loads" conveniently, namely a sensible heat load involving changes of air dry bulb temperature at constant moisture content and latent heat load involving moisture content changes at constant dry bulb temperature.

Incoming air must therefore be capable of offsetting both these loads if room conditions are to be stable.

2.4.1 Sensible heat load

The heat loss or gain to the room at constant moisture content can be expressed in watts and so for a room temperature to t_r and supply air temperature of t_a the following expression must apply:

$$q_s = mC_p(t_r - t_a) \tag{2.14}$$

where:
q_s = sensible heat load
m = mass of supply air flow, and
C_p = specific heat of humid air

Obviously if the heat load is positive then $t_a < t_r$.

This implies, on the psychrometric chart that the air supply condition in winter is to the right of the room condition and to the left in summer.

Thus:
$$q_s = m.c(t_r - t_a) \tag{2.15}$$

or
$$q_s = m(h_r - h_a) \tag{2.16}$$

2.4.2 Latent heat load

An alternative way of expressing a change in room moisture content is to refer to the energy input required to evaporate that quantity of water based on the latent heat of evaporation at that temperature.

Thus the air supplied to the room must have an ability to absorb this quantity of evaporated water, thus maintaining the room condition.

The latent heat load may be expressed as

$$q_L = \text{kg of water evaported} \times \text{latent heat of evaporation /kg} \qquad (2.17)$$

If the supply air is at a moisture content of g_a kgkg^{-1} and the room design point is g_r kgkg^{-1} then the ability of the incoming air to absorb moisture is defined by:

Mass flow rate supply air × $(g_r - g_a) = m(g_r - g_a)$ kgkg^{-1} (2.18)

Hence the latent heat load represented by this moisture difference is: $m(g_r - g_a)$ kgkg^{-1} x latent heat of evaporation kg^{-1} and for design conditions to be maintained:

$$q_L = m(g_r - g_a)h_{fg} \qquad (2.19)$$

where h_{fg} is latent heat of evaporation at room temperature.

For a room with a positive latent heat gain the supply point must lie below the room design point.

2.4.3 Relation between room state and supply air state

As the supply air must offset both the sensible and latent heat loads simultaneously it follows that the air supply state can be defined in terms of dry bulb temperature and moisture content and the two heat loads.

sensible $q_s = mc(t_r - t_a)$

latent $q_L = m(g_r - g_a)h_{fg}$

If t_a, g_a, and m are the only variables

$$t_a = t_r - \frac{q_s}{mc} \quad \text{and} \quad g_a = g_r - \frac{q_L}{mh_{fg}}$$

These expressions confirm that the larger the mass flow rate the closer can be the supply and room points.

2.4.4 Room supply line and sensible heat ratio

As shown above there are an infinite number of supply air state points that would offset both the latent and sensible heat loads. All are on a straight line drawn in the t - g plane on a psychrometric chart.

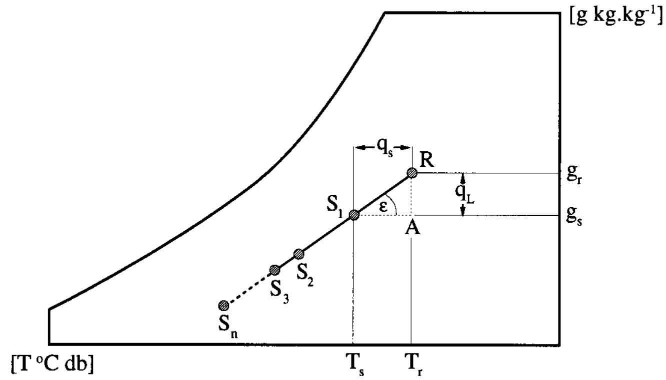

Fig 2.11

Now $q_L = (h_R - h_A)$ and, $q_S = (h_A - h_S)$

The room supply line, sometimes known as the room ratio line has a slope defined by

$$\tan \in = \frac{q_l}{q_s} \qquad (2.20)$$

An alternative definition is to take the sensible heat ratio coefficient as

$$SHR = \frac{q_s}{(q_s + q_l)} \qquad (2.21)$$

2.4.5 Latent heat of evaporation

The energy required to evaporate a unit mass of water, h_{fg} is temperature dependent. Some common values are presented in the following table.

Temperature (^0C)	Latent Heat of evaporation (kJ/kg)
0	2501
5	2489
20	2454
30	2430
50	2382
100	2257
150	2114
200	1940

Table 2.1

Tutorial questions 1

Use of psychrometric data

1 Using the CIBSE psychrometric chart complete the following table of values for a moist air stream.

Dry bulb temp ^{0}C	Wet bulb temp ^{0}C	Specific enthalpy kJ/kg	Specific volume m^3/kg	% saturation	Moisture content kg/kg
40^{0}C-	-	-	-	-	0.01
40^{0}C	20^{0}C	-	-	-	-
40^{0}C	-	-	-	30%	-
15^{0}C	-	-	0.82	-	-
25^{0}C	15^{0}C	-	-	-	-
30^{0}C	-	30	-	-	-
50^{0}C	-	120	-	-	-

2 Using a psychrometric chart write down the dew point temperature for the following moist air conditions.

1 45^{0}Cdb, 0.010 kg/kg moisture content
2 15^{0}Cdb, 10 Cwb
3 50Cdb, 120 kJ/kg specific enthalpy
4 15^{0}Cdb, 0.82m^3/kg specific volume
5 40^{0}Cdb, 30% saturation.

3 Calculate the humid specific heat for each of the air conditions in Question 2.1.

4 Calculate the specific enthalpy of each of the air conditions in Question 2.1.

Tutorial questions 2

Mixtures

1 Show that the final mixture state between two moist air streams can be represented by a point on a straight line on a psychrometric chart linking the individual mixed air conditions.

2 A stream of moist air at a state of 21^0C dry bulb and 14.5^0C wet bulb mixes with another stream of moist air at a state of 28^0Cdb and 20.2^0C wet bulb, the respective masses of the associated dry air being 3kg and 1kg. From charts or tables calculate the mixed air conditions.

3 A stream of moist air at a state of 25^0Cdb and 40kJ/kg specific enthalpy is to be mixed with an air stream so that the final mixture conditions become 20^0Cdb and 12^0C wet bulb. If the mixture by mass of re-circulated air to fresh air is 75% to 25%, calculate the supply air conditions.

4 Calculate the gradient of the straight line on a psychrometric chart in terms of moisture content per ^{o}Cdb joining supply air conditions to room conditions if the final mixture condition is to be 21^0Cdb and 50% saturation and supply conditions are:-

1 8^0Cdb, 5^0C wet bulb
2 30% saturation, 5kJ/kg specific enthalpy
3 5^0 wet bulb, 0.8m^3/kg specific volume
4 15kJ.kg specific enthalpy, 0.82m^3/kg specific volume

Tutorial questions 3

Sensible heating and cooling

1 Calculate the load in a heater coil which raises 2m^3/sec of moist air, initially at a state of 15^{o}C, 70% saturation by 25^{o}C.If low-pressure hot water is used in the heater battery, entering at 85^{o}C and leaving at 75^{o}C, calculate the necessary water flow rate.

2 In Question 1 the flow rate of heater water is reduced by 25%. Calculate:

a) the reduction in air temperature rise

b) the required water temperature at inlet to the heater if 25^{o}C air temperature rise is to be achieved. Assume all other variables unchanged.

3 Moist air at 25^{o}C wet bulb and 0.014kg/kg moisture content is to be cooled by a chilled water cooler whose inlet and outlet temperatures are 8^{o}C and 12^{o}C. Plot air flow rate against cooling water flow rate per ^{o}Cdb of air cooling and determine the lowest air temperature that could be achieved by such a system without a change in air stream humidity.

4 An office has a sensible heat gain of 10 kW when the room-air temperature is 20^{o}C db. Calculate the necessary mass flow rate of supply air to maintain the room at the design temperature when the supply-air temperature can be 12 ^{o}C db.

Outline solution for 4:

(2.14) $SHG = q_{shg} = mc_p(t_r + t_s)$ is rearranged to

$$m = \frac{q_{shg}}{c_p(t_r + t_s)} = \frac{10kW}{1.2\frac{kJ}{kgK} \times (20-12)} = 1.04kg/s$$

Tutorial questions 4

Humidification and dehumidification

1 Define

a) Dew point temperature
b) Apparatus dew point temperature
c) Contact factor, or by pass factor
d) Spray chamber, effectiveness
e) Humidifying efficiency
f) Adiabatic humidification

2 Show that both cooling coil and a spray chamber may be used for dehumidification

3 2.5m^3/s of moist air at a state of 30^{o}Cdb and 19^{o}C wet bulb pass a cooler coil and leave at 15^{o}Cdb and 8g/kg moisture content.

Calculate:

a) apparatus dew point
b) contact factor
c) cooling load
d) chilled water mass flow rate if a temperature difference of 8^{o}C is recorded across the cooling coil water inlet and exit

4 Spray water at 5^{o}C is used in an air washer intended to dehumidify 2.0m^3/s of moist air entering at a state of 28^{o}Cdb and 19^{o}C wet bulb. If the efficiency of the washer is 90%, calculate the air state at exit from the washer and the cooling load involved. Calculate the water removal rate necessary.

5 2.3m^3/s of moist air at a state of 15^{o}Cdb and 19^{o}C wet bulb enters a spray chamber of an air washer. The humidifying efficiency is 90%, the spray water is re-circulated and the make up water is supplied at 9^{o}C to make up evaporation losses. Calculate the state of the air leaving the washer and the make up water flow rate.

6 3m^3/s of moist air at 25^{o}Cdb and 15^{o}C wet bulb passes through a spray chamber where 0.009kg of water are injected into the air stream and totally evaporated. Calculate the air exit state if the injected water is at:

a) 0^oC
b) 10^oC
c) 50^oC
d) 100^oC

7 Dry saturated steam may be generated at a range of temperatures and pressures from 100^oC up to 234^oC and can be injected into an air stream to increase humidity. On a CIBSE chart plot these processes for a range of steam temperatures if the initial moist air state is 30^oCdb and 12^oC wet bulb and 0.010kg/s of steam is injected per m^3/s of dry air passing. Calculate final moist air condition.

Take specific heat water as 1.89kJ/kg
specific heat of dry air as 1.01kJ/kg
enthalpy of dry saturated steam at 100^oC = 2676kJ.kg
enthalpy of dry saturated steam at 234^oC = 2800kJ/kg