(*f*) A mass balance must be struck to determine the rise in moisture content in the room as a consequence of the evaporation corresponding to the liberation of the latent heat gains:

latent heat gain in kW = (kg of dry air per hour delivered to the room) × (the moisture pick-up in kg of water per kg of dry air) × (the latent heat of evaporation of water in kJ per kg of water)

$$5.0 = 3.063 \times (g_r - 0.006\,831) \times 2454$$

whence

$$g_r = 0.007\,496 \text{ kg per kg dry air}$$

From tables or from a chart it may be found that at a state of 20°C dry-bulb and 7.496 g per kg dry air, the relative humidity is about 51 per cent and, for use in Example 3.14(*b*), $h_r = 39.14$ kJ kg^{-1}.

3.10 Mixing and adiabatic saturation with reheat

Figure 3.13(*a*) shows a plant arrangement including an air washer which, although undesirable for comfort air conditioning, is retained here to illustrate the psychrometry involved. Air at state R is extracted from a conditioned room and partly recirculated, the remainder being discharged to atmosphere. The portion of the extracted air returned to the air conditioning plant mixes with air at state O, drawn from outside, and forms a mixture state M. The air then passes through an air washer, the spray water of which is only recirculated and adiabatic saturation occurs, the state of the air changing from M to W (see Figure 3.13(*b*)) along a line of constant wet-bulb temperature (see sections 3.5 and 3.6). An extension of the line MW cuts the saturation curve at a point A, the apparatus dew point. To deal with a particular latent heat gain in the conditioned room it is necessary to supply the air to the room at a moisture content g_s, it being arranged that the difference of moisture content $g_r - g_s$, in conjunction with the mass of air delivered to the room, will offset the latent gain. In other words, the air supplied must be dry enough to absorb the moisture liberated in the room.

It is evident that the moisture content of the air leaving the washer must have a value g_w, equal to the required value, g_s. This is amenable to calculation by making use of the definition of the effectiveness of an air washer, in terms of g_a, g_w and g_m (see section 3.5).

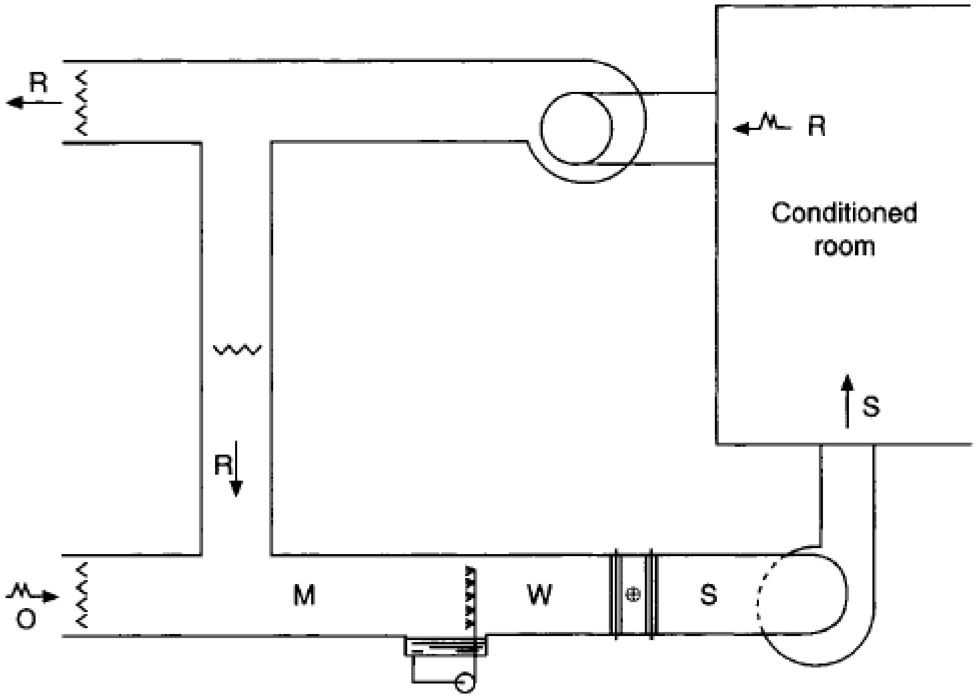
EXAMPLE 3.14

If the room mentioned in example 3.13 is conditioned by means of a plant using a mixture of recirculated and fresh air, of the type illustrated in Figure 3.13(*a*), calculate:

(*a*) the percentage of the air supplied to the room by mass which is recirculated, and
(*b*) the humidifying efficiency of the air washer.

Answer

(*a*) Since the wet-bulb scale is not linear, it is not accurate enough to calculate the mixing proportions on this basis. Instead, one must make use of changes of enthalpy or moisture content. Bearing in mind that lines of constant enthalpy are not parallel to lines of constant wet-bulb temperature, some slight inaccuracy is still present if the assumption is made that the change of state accompanying a process of adiabatic saturation is along a line of constant enthalpy. However, this is unavoidable, and so such an assumption is made.



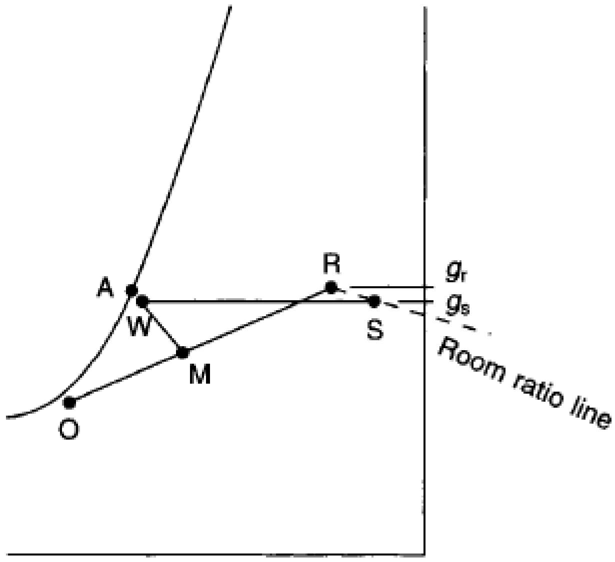


Fig. 3.13 (a) Plant arrangement to permit variable mixing proportions of fresh and recirculated air. (b) Psychrometry for example 3.14.

Referring to Figure 3.13(*b*) it can be seen that

$$h_a \simeq h_w \simeq h_m$$

From tables and Figure 3.12(*b*) it is established that h_w (at 12°C dry-bulb and 6.831 g kg^{-1}) is 29.30 kJ kg^{-1}.

From the principles set out in section 3.2, governing the change of state associated with a mixing process, it is clear that the percentage of recirculated air, by mass,

$$= \frac{h_m - h_o}{h_r - h_o} \times 100$$

$$= \frac{29.30 - 0.298}{39.14 - 0.298} \times 100$$

$$= 75 \text{ per cent}$$

Thus, 75 per cent of the air supplied to the room, if recirculated and mixed with 25 per cent of air from outside, will have an enthalpy of 29.30 kJ kg^{-1} and a wet-bulb of 10°C (sling). If adiabatic saturation is then to produce a state of 12°C dry-bulb and 6.831 g kg^{-1}, the humidifying efficiency of the washer used can no longer be the value used for example 3.13, namely, 85 per cent. An entirely different washer must be used for the above calculations to be valid and this must have an effectiveness which may be calculated as follows:

(*b*) Since efficiency is expressed in terms of moisture content, it is necessary to determine the value of g_m, the values of g_a and g_w being already known.

$$g_m = 0.75 g_r + 0.25 g_o$$
$$= 0.75 \times 7.497 + 0.25 \times 2.137$$
$$= 6.157 \text{ g kg}^{-1}$$

$$\text{Humidifying efficiency} = \frac{g_w - g_m}{g_a - g_m} \times 100$$

$$= \frac{6.831 - 6.157}{7.659 - 6.157} \times 100$$

$$= 45 \text{ per cent}$$

In practical terms, this is a low efficiency.

If the washer used in this example had an efficiency of 85 per cent, as in example 3.13, then the calculations would not have been so easy. The line AWM would have had to have been at a lower wet-bulb value in order to fulfil two requirements:

(i) $g_w = 6.831 \text{ g kg}^{-1}$

(ii) $\frac{g_w - g_m}{g_a - g_m} \times 100 = 85$ per cent

For this to be the case, the dry-bulb temperature of W must obviously be less than 10°C. The easiest way to achieve a practical solution is by drawing a succession of lines representing processes of adiabatic saturation on a psychrometric chart and calculating several values of efficiency until one of acceptable accuracy is obtained.

3.11 The use of dry steam for humidification

It is only if the air can accept the additional moisture, that humidification may be achieved by the injection of spray water or dry steam. If the state of the air into which it is proposed to inject moisture is saturated, or close to saturation, some or all of the moisture added will not be accepted and will be deposited downstream in the air handling plant or the duct system. It is therefore essential to ensure that the airstream is sufficiently heated prior to moisture injection.

EXAMPLE 3.15

A room is to be maintained at a state of 20°C dry-bulb and 50 per cent saturation by a plant handling 0.5 $m^3 s^{-1}$ of outside air at a state of –2°C saturated. The airstream is heated to a temperature warm enough to offset a heat loss of 2.5 kW and dry steam is then injected to maintain the humidity required in the room. Calculate the supply air temperature and the heating and humidification loads. See Figure 3.14.

Answer

From psychrometric tables or a psychrometric chart, air at the outside state has a moisture content of 3.205 g kg^{-1}, an enthalpy of 5.992 kJ kg^{-1} and a specific volume of 0.7716 $m^3 kg^{-1}$. Assuming specific heats of 1.012 and 1.89 kJ $kg^{-1} K^{-1}$, respectively, for dry air and water vapour, the humid specific heat of the fresh air handled is

$$1 \times 1.012 + 0.003\,205 \times 1.89 = 1.018 \text{ kJ kg}^{-1} \text{ K}^{-1}$$

The heat loss is offset by the supply of air at a temperature t_s, warmer than the room temperature of 20°C. Hence

$$2.5 = (0.5/0.7716) \times 1.018 \times (t_s - 20)$$

whence t_s = 23.8°C.

From tables or a chart the enthalpy at state B, leaving the heater battery, is 32.10 kJ kg^{-1}. See Figure 3.14. Hence the heater battery load is

$$(0.5/0.7716) \times (32.10 - 5.992) = 16.92 \text{ kW}$$

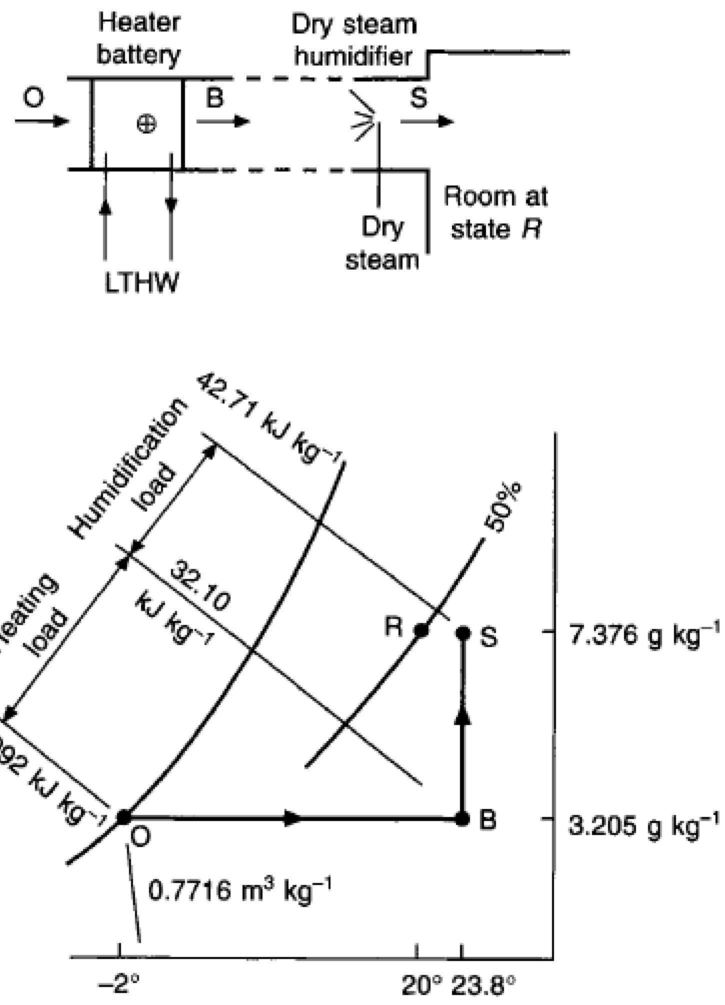


Fig. 3.14 The use of dry steam for humidification. See Example 3.15.

Alternatively

$$(0.5/0.7716) \times 1.018 \times (23.8 + 2) = 17.02 \text{ kW}$$

The first method is preferred because enthalpy values are based on well-established thermodynamic properties of dry air and water vapour whereas, on the other hand, the values of the specific heats used for the second method may not be exactly correct.

Assuming the change of state resulting from the injection of dry saturated steam is up a dry-bulb line, the state of the air supplied to the room is 23.8°C dry-bulb and 7.376 g kg^{-1}, at which the enthalpy is determined as 42.71 kJ kg^{-1} from tables or a chart. Hence the humidification load is

$$(0.5/0.7716) \times (42.71 - 32.10) = 6.88 \text{ kW}$$

Exercises

1. Dry saturated steam at 1.2 bar and 104.8°C is injected at a rate of 0.01 kg s^{-1} into an airstream having a mass flow rate of dry air of 1 kg s^{-1} and an initial state of 28°C dry-bulb, 11.9°C wet-bulb (sling). Calculate the leaving state of the airstream if all the injected steam is accepted by it. Use equation (2.24) as necessary.

Answers

29.3°C, 11.937 g kg^{-1}.

2. Air at 40°C dry bulb temperature and 30% relative humidity is passed through an adiabatic air washer at the rate of 28 m^3/min. If the effectiveness of the air washer is 80%, find the conditions of the air leaving the air washer, and the amount of water vapor added to the air per minute.

Answer

W_2= 0.019 kg/$kg_{d.a}$, t_{d2}= 28°C, ϕ_2= 80%, $\dot{m}_s$= 0.154 kg/min

3. An air conditioning system controls the indoor conditions of a room at 20°C dry bulb temperature and 50% relative humidity, when the outdoor conditions are at 5°C dry bulb temperature and 70% relative humidity. 2 m^3/s of recycled air from the room is mixing with 1 m^3/s of the fresh air, the mixture then flows across a heater and come out of it at 27°C, and supply to the room. Sketch the process on the psychrometric chart and determine:

(a) the amount of heat that gives the heater to the air in kW.

(b) the heating load of the room in kW.

Answer

45.13 kW, 14.56 kW

4. Air at 28°C dry bulb temperature and 50% relative humidity passes through a cooling coil at a rate of 1 m^3/s, the air leaves the coil at 10°C dry bulb temperature and 0.007 kg/$kg_{d.a}$ moisture content. Calculate the following by using the psychrometric chart.

(a) mass flow rate of the air (b) total heat removed from the air

(c) contact factor of the coil (d) rate of condensing of water vapor

Answer: 1.150 kg/s, 34.5 kW, 0.81, 20.286 kg/h.

5. 0.95 m^3/s of outside air passes over a cooling coil. The outdoor air is at 35^oC dry bulb and 25^oC wet bulb temperature, and the conditioned space is being maintained at 26^oC dry bulb temperature and 45% relative humidity. the sensible heat ratio is calculated as 0.72. the air leaving the coil is 90% saturated.

(a) find the apparatus dew point, and the temperature of the air leaving the coil

(b) how much cooling in kW is the unit doing

(c) how much moisture in $kg/kg_{d.a}$ is condensed out of the incoming air per hour.

Answer

(a) 8^oC, 10.4^oC (b) 51.39 kW (c) 34.47 kg/h

6. The sensible heat gain of a room is 4.8 kW and its latent heat gain is 1.4 kW. A conditioned air supply of 0.5 m^3/s is to be delivered to the room. If the room is to be maintained at 25^oC DBT, find the relative humidity that will result in the conditioned room if the air supply is 17^oC and 90% RH.

Answer

60%

7. Air enters a chamber at 10^oC DBT and 5^oC WBT at a rate of 100 m^3/min. The barometer reads a pressure of 1.01325 bar. While passing through the chamber, the air absorbs sensible heat at the rate of 40 kW and picks up 45 kg/h of saturated steam at 105^oC. Determine the dry and wet bulb temperatures of the air leaving the chamber.

Answer

26.5^oC, 18.1^oC