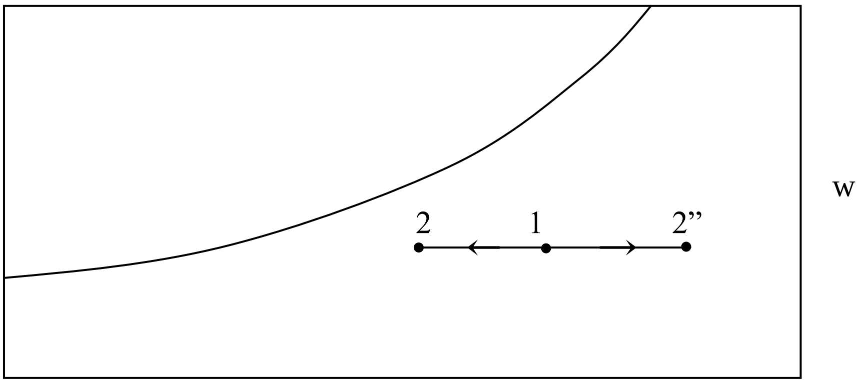
6.6 Psychrometric processes

6.6.1 Sensible heating or cooling – is a constant *w* process.



Dry bulb temperature, t

$1 \longrightarrow 2''$ is a sensible heating process
$1 \longrightarrow 2$ is a sensible cooling process

Consider a sensible cooling process (1 – 2)
Previously shown, $h = c_{pa} t + (c_{pv} t + h_{fg,0}) w = c_{pm} t + h_{fg,0} w$, then the sensible heat transfer rate is,

$$Q_s = m_a (h_2 - h_1)$$
$$= m_a (c_{pm} t_2 + h_{fg,0} w) - (c_{pm} t_1 + h_{fg,0} w))$$

i.e.

$$Q_s = m_a c_{pm} (t_2 - t_1) \quad \ldots\ldots(21)$$

where $c_{pm} = c_{pa} + c_{pv}$

Alternately,

$$Q_s = \rho_a V c_{pm} (t_2 - t_1)$$

At t = 24 ^oC, 50 % RH :--

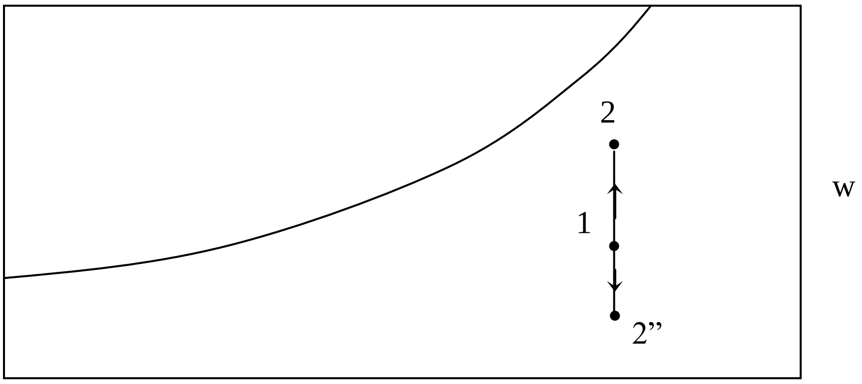
$\rho_a = 1.17$ kg/m^3, $c_{pm} = 1.02$ kJ/kgK, then
$\rho_a c_{pm} = 1.196 \approx 1.2$ kJ/K.m^3

Then,

$$\boxed{Q_s = 1.2 V (t_2 - t_1)}$$

where V = volume flow rate (of dry air), L/s
Q_s = sensible heat transfer rate, W (+ve means sensible heating where heat is added to mixture; – ve indicates sensible cooling of mixture)
t = dry bulb temperature, ^oC

6.6.2 Latent heat process – humidification or dehumidification



It is a constant dry bulb temperature process (almost never occurs in practice) !

$1 \longrightarrow 2$ humidification (moisture addition)
$1 \longrightarrow 2”$ dehumidification (moisture extraction)

Consider the humidification process (1 to 2), the latent tranfer rate to mixture is,

$$Q_L = m_a (h_2 - h_1)$$

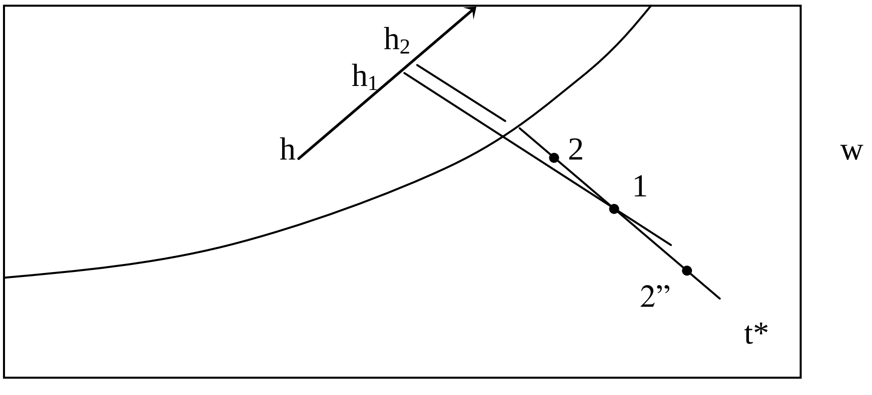
or

$$Q_L = m_a h_{fg,0C} (w_2 - w_1) = \rho_a V h_{fg,0C} (w_2 - w_1) \quad \text{………..……} (22)$$

$$\boxed{Q_L = 2.9\, V (w_2 - w_1)}$$

where V = volume flow rate (of dry air), L/s
Q_L = latent heat transfer rate, W (+ve means latent heat addition as a result of moisture being added to the mixture – ie humidification)
w = humidity ratio, kg_v / kg_{DA}

6.6.3 Adiabatic saturation process – constant wet bulb temperature



Occurs along the a constant wet bulb temperature line t*, where at any point along this line, $h = w\, h_f^* = w\, c_{pf}\, t^*$.

Consider an adiabatic saturation process from 1 to 2, we can write,

$$h_2 - h_1 = (w_2 - w_1)\, h_f^* = (w_2 - w_1)\, c_{pf}\, t^*$$

<u>For example</u>,

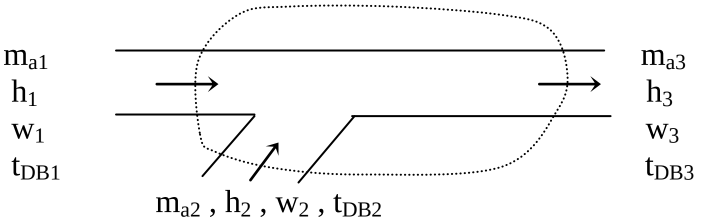
$t^* = 20$ C, $t_{DB1} = 35$ C, $t_{DB2} = 25$ C

From psychrometric chart, $w_2 = 0.0126$, $w_1 = 0.0085$. Then,

$$h_2 - h_1 = (0.0126 - 0.0085)\ 4.186\ (20)$$
$$= 0.343 \text{ kJ/kg} \qquad (\text{compare with } h_1 = 57.8 \text{ kJ/kg})$$

In conclusion, $h_2 \neq h_1$, ie constant wet bulb temperature lines <u>deviate</u> from the constant enthalpy lines on the psychrometric chart.

<u>6.6.4 Adiabatic mixing process</u>



<u>step 1</u> mass balance for the air

$$m_{a1} + m_{a2} = m_{a3} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(23)$$

<u>step 2</u> mass balance for vapour

$$m_{v1} + m_{v2} = m_{v3}$$

but ($m_v = m_a w$), thus, $\quad m_{a1} w_1 + m_{a2} w_2 = m_{a3} w_3 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(24)$

or, $\quad w_3 = \dfrac{m_{a1}}{m_{a3}} w_1 + \left(1 - \dfrac{m_{a1}}{m_{a3}}\right) w_2 \quad$ where $m_{a2} = m_{a3} - m_{a1}$

Thus, $\quad \dfrac{m_{a1}}{m_{a3}} = \dfrac{w_3 - w_2}{w_1 - w_2} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots...(25)$

<u>Step 3</u> – Apply enthalpy balance

$$m_{a1} h_1 + m_{a2} h_2 = m_{a3} h_3$$

or $\quad \dfrac{m_{a1}}{m_{a3}} = \dfrac{h_3 - h_2}{h_1 - h_2} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(26)$

or $\quad h_3 = \dfrac{m_{a1}}{m_{a3}} h_1 + \left(1 - \dfrac{m_{a1}}{m_{a3}}\right) h_2 \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (27)$

using $h = c_{pm}\, t + h_{fg,0C}\, w$, then

$$c_{pm}\, t_3 = c_{pm} \left[\frac{m_{a1}}{m_{a3}} t_1 + \left(1 - \frac{m_{a1}}{m_{a3}}\right) t_2 \right] + h_{fg.0C} \left[\frac{m_{a1}}{m_{a3}} w_1 + \left(1 - \frac{m_{a1}}{m_{a3}}\right) w_2 \right] - h_{fg,0C}\, w_3$$

ie,

$$c_{pm}\, t_3 = c_{pm}\left[\frac{m_{a1}}{m_{a3}} t_1 + \left(1-\frac{m_{a1}}{m_{a3}}\right) t_2\right]$$

or

$$t_3 = \frac{m_{a1}t_1 + m_{a2}t_2}{m_{a1} + m_{a2}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(28)$$

Example

1000 L/s of air at 38 C dry bulb (DB) and 24 C wet bulb (WB) is mixed with 500 L/s of air at 16 C DB and 10 C WB. The process is adiabtaic, a steady flow process and at standard sea level pressure. Find the condition of the mixed stream.

t_1 = 38 C, t_1^* = 24 C, t_2 = 16 C, t_2^* = 10C.

analytical solution – from psychrometric chart,
$v_1 = 0.9\ \mathrm{m^3/kg}$, $v_2 = 0.825\ \mathrm{m^3/kg}$

$$m_{a1} = \frac{V_1}{v_1} = \frac{1000(10^{-3})}{0.9} = 1.11 \text{ kg/s} \quad ; \qquad m_{a2} = \frac{V_2}{v_2} = \frac{500(10^{-3})}{0.825} = 0.61 \text{ kg/s}$$

Then $m_{a3} = m_{a1} + m_{a2} = 1.11 + 0.61 = 1.72$ kg/s

Using eqn. 28, $t_3 = \dfrac{1.11(38) + 0.61(16)}{1.11 + 0.61} = 30.24$ C

Since point 3 lies on a straight line between points 1 and 2 on the psychrometric chart,
$v_3 = 0.872\ \mathrm{m^2/kg}$

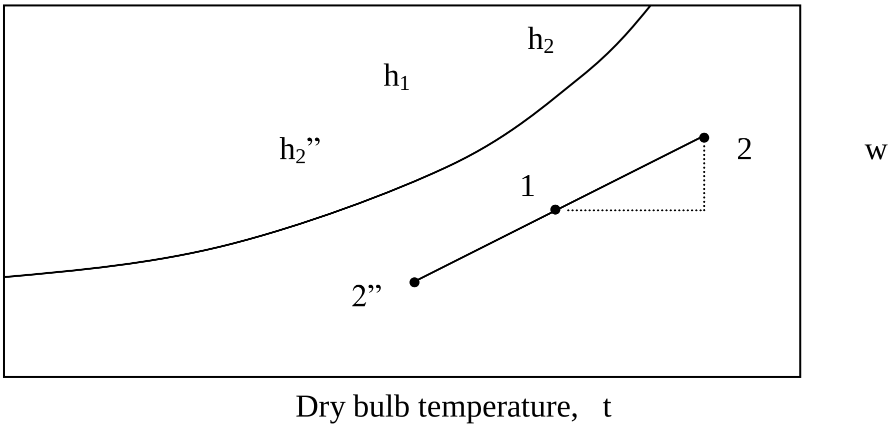
Thus, $V_3 = m_{a3}\, v_3 = 1.72\ (0.872) = 1497$ L/s

Using eqn. 25, $w_3 = w_2 + \left(\dfrac{m_{a1}}{m_{a2}}\right)(w_1 - w_2) = 0.13 + \left(\dfrac{1.11}{0.16}\right)(0.13 - 0.0052) = 0.0103\ \mathrm{m^3/kg}$

Using eqn. 26, $h_3 = h_2 + \left(\dfrac{m_{a1}}{m_{a2}}\right)(h_1 - h_2) = 29 + \left(\dfrac{1.11}{0.16}\right)(72 - 29) = 56.8$ kJ/kg

KNOWING w_3, h_3 use chart to find, $t_3 = 30\ ¼$ C and $t_3^* = 19\ ¾$ C

6.6.5 Total heating or cooling process

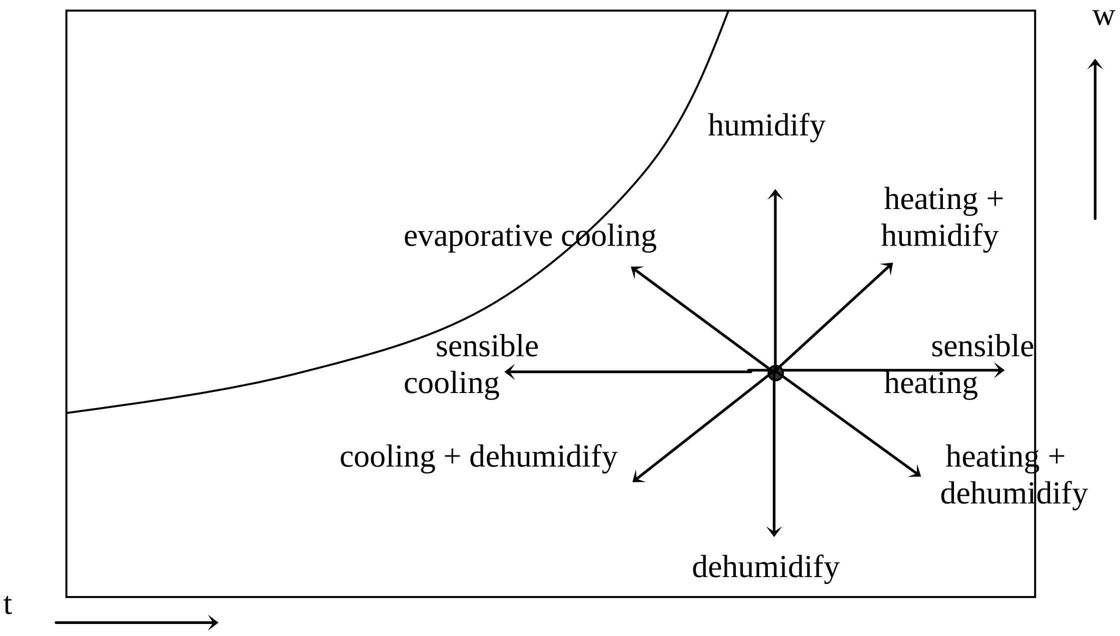


1 ⟶ 2 is heating
1 ⟶ 2” is cooling

Consider the total heating process 1 to 2, the total heat transfer rate to the air is

$$\begin{aligned} Q &= m_a (h_2 - h_1) = m_a (h_3 - h_1) + m_a (h_2 - h_3) \\ &= m_a c_{pm} (t_3 - t_1) + m_a h_{fg,0C} (w_2 - w_3) \qquad \text{(but } t_3 = t_2,\ w_3 = w_1\text{).} \\ &= m_a c_{pm} (t_2 - t_1) + m_a h_{fg,0C} (w_2 - w_1) \\ &= Q_{\text{sensible}} + Q_{\text{latent}} \\ &= 1.2\, V (t_2 - t_1) + 2.9\, V (w_2 - w_1) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (29) \end{aligned}$$

6.6.6 General process (summary)



6.6.7 Sensible heat factor (SHF)

$$\text{SHF} = \frac{Q_s}{Q_s + Q_L}$$

But $Q_s = m_a c_{pm} (t_2 - t_1)$

$Q_L = m_a h_{fg,0C} (w_2 - w_1)$

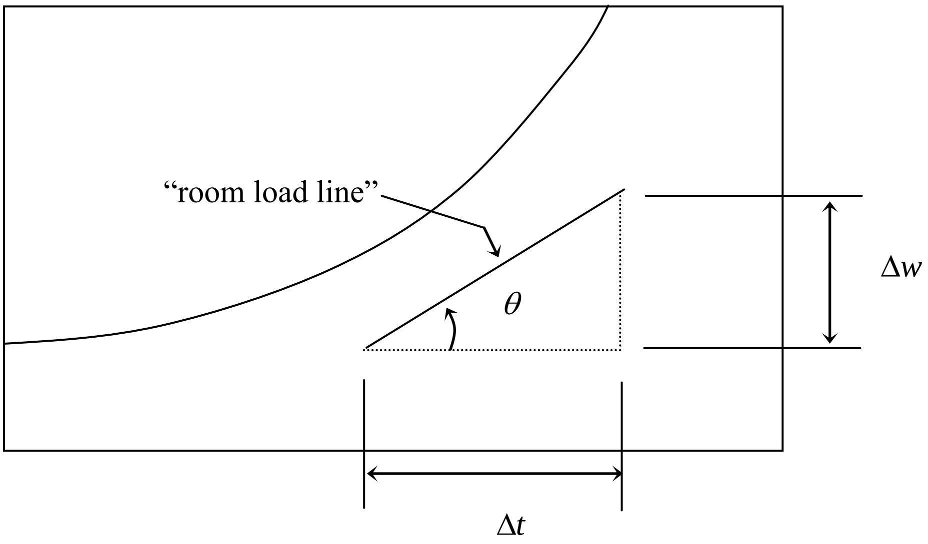
$$\text{SHF} = \frac{c_{pm}(t_2 - t_1)}{c_{pm}(t_2 - t_1) + h_{fg,0C}(w_2 - w_1)}$$

$$\text{SHF} = \frac{1}{1 + \frac{h_{fg,0C}}{c_{pm}} \cdot \frac{\Delta w}{\Delta t}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (30)$$

$\frac{\Delta w}{\Delta t} = \tan\theta$ ………. Substitute into eq. 30, we obtain

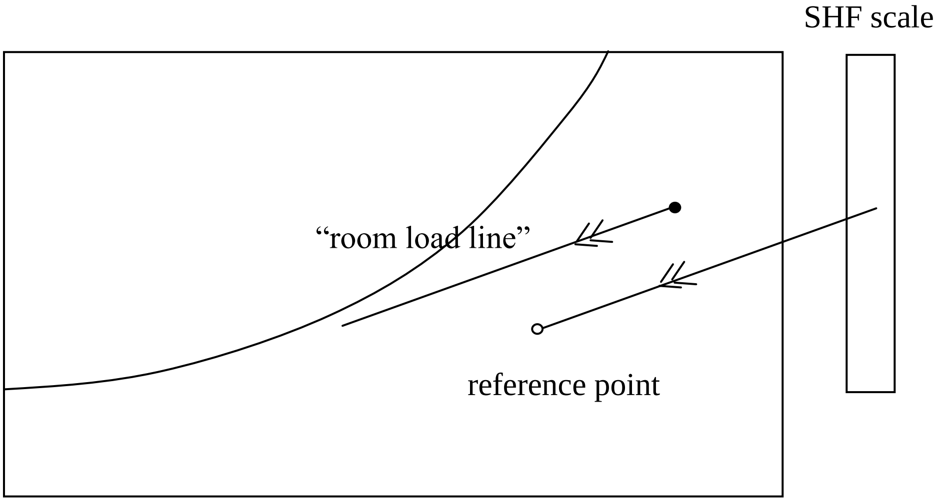
$$\tan\theta = \frac{c_{pm}}{h_{fg,0C}} \left(\frac{1}{SHF} - 1 \right)$$

where, $c_{pm} \approx 1.02$ kJ/kgK
$h_{fg,0C} \approx 2501$ kJ/kg

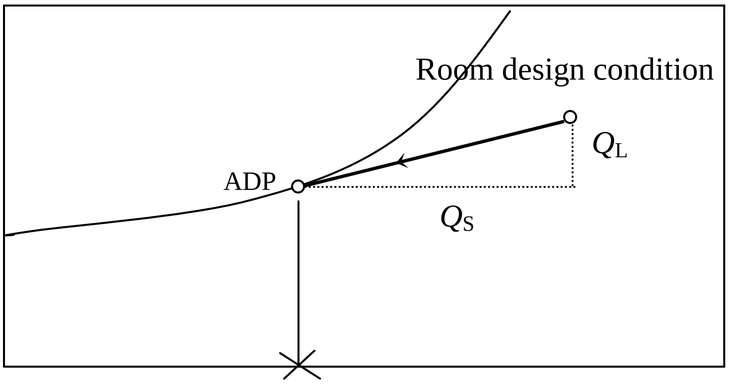


Thus, once we know

1) initial or final state of air
2) sensible heat factor, SHF



What does the "room load line" means ?

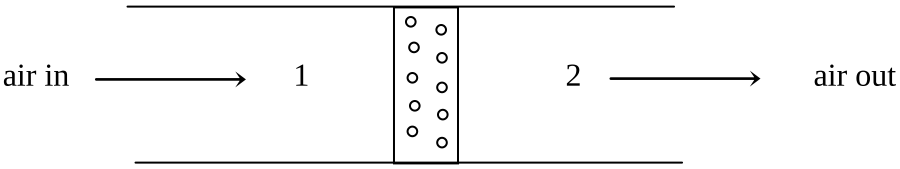


Supply air temperature;
At "Apparatus Dew Point Temperature", ADP

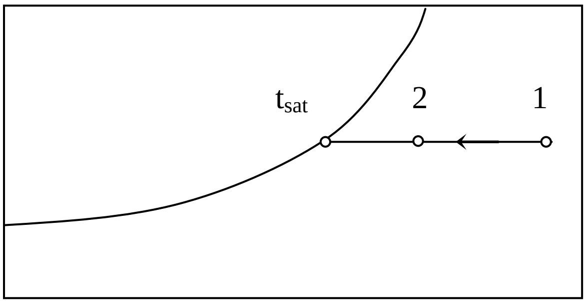
7. Air Conditioning

7.1 Basic air conditioning equipment

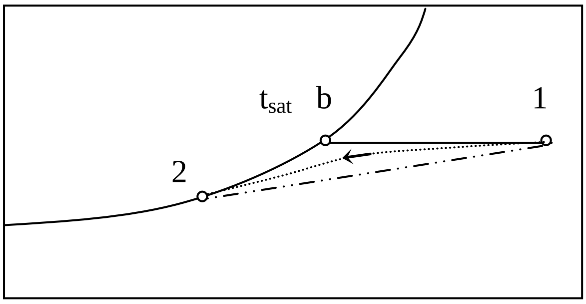
7.1.1 Cooling coil



(a) If $t_2 > t_{saturation}$ (ie $t_2 > t_{DP}$) then only sensible cooling occurs

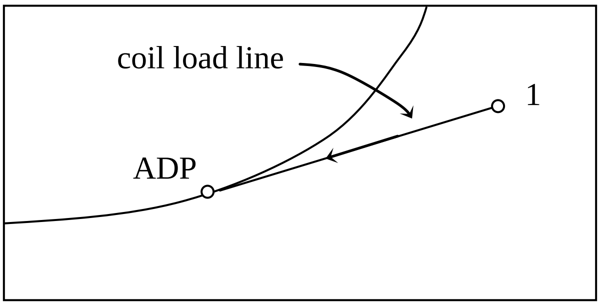


(b) If $t_2 < t_{sat}$ – then both sensible cooling and dehumidification occur,

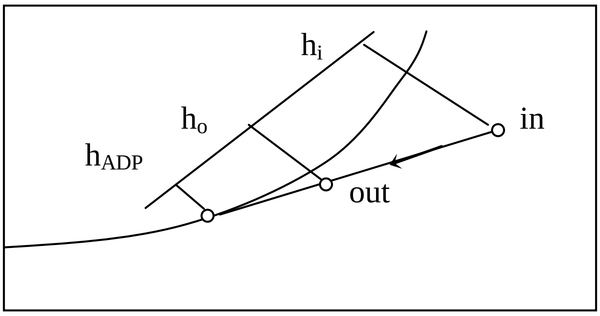


1 – b – 2 at any section of coil, the air is at a uniform dry bulb temperature
1 – 2 (straight line) occurs if the wetted surface is at constant temperature – <u>commonly shown</u>
1 – 2 (curved line) is actual process.

(i) Apparatus dew point (ADP)



(ii) Coil effectiveness (or bypass factor)



coil effectiveness,

$$\eta_C = \frac{h_i - h_o}{h_i - h_{ADP}} = \frac{w_i - w_o}{w_i - w_{ADP}} = \frac{t_i - t_o}{t_i - t_{ADP}} \quad \text{………………….(31)}$$

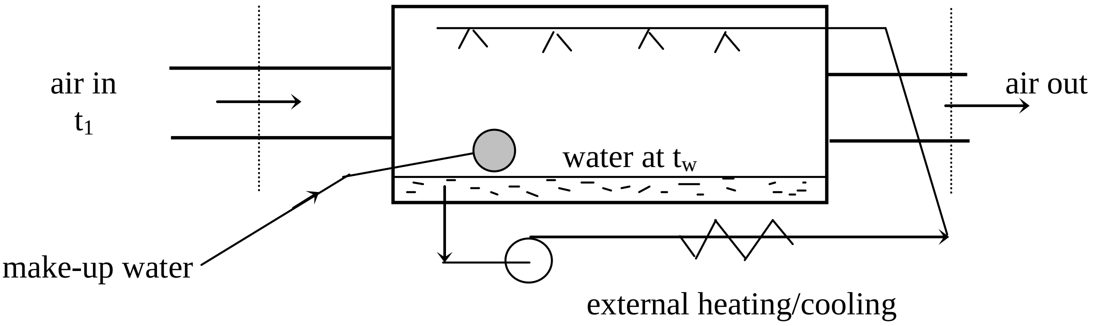
Bypass factor (BPF),

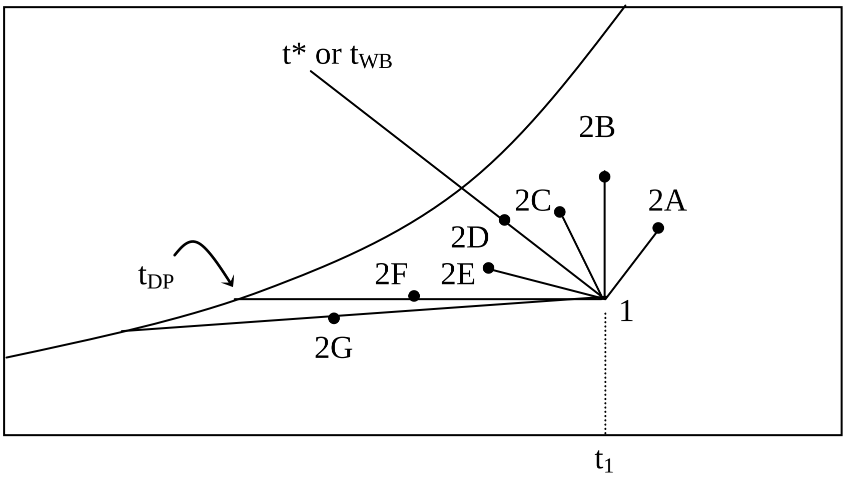
$$\text{BPF} = \frac{h_o - h_{ADP}}{h_i - h_{ADP}} \quad \text{or} \quad \boxed{\eta_C = 1 - \text{BPF}}$$

Typically BPF is of the order of 0.10. It is affected by,

(i) air velocity through coil
(ii) free surface between coil tubes
(iii) number of rows of coils

7.1.3 Air washers





Process 1 – 2A is heating and humidifying ($t_w > t_1$); water is externally heated.

Process 1 – 2B is humidifying ($t_w = t_1$);

Q = m ($h_2 - h_1$) , simply because $h_2 > h_1$ means that external heating must occur.
Remember that latent heat is added to air !

Process 1 – 2C is cooling and humidifying ($t_{WB} < t_w < t_1$); water is externally heated.

Process 1 – 2D is adiabatic saturation ($t_w = t_{WB}$) where no external heating or cooling of water occurs.

Process 1 – 2E is cooling and humidifying ($t_{DP} < t_w < t_{WB}$); water is externally cooled.

Process 1 – 2F is sensible cooling ($t_w = t_{DP}$); water is externally cooled.

Process 1 – 2G is cooling and dehumidifying ($t_w < t_{DP}$); water is externally cooled.

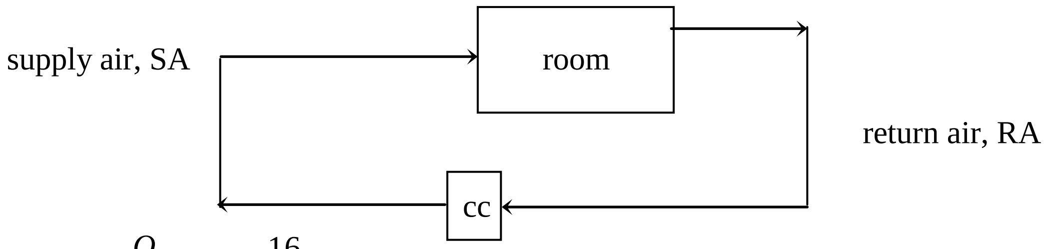
7.2 Applications

For all examples, consider a room with Q_S = 16 kW, Q_L = 7 kW
Room design conditions ; 24 C dry bulb, 50 % RH.
Determine,

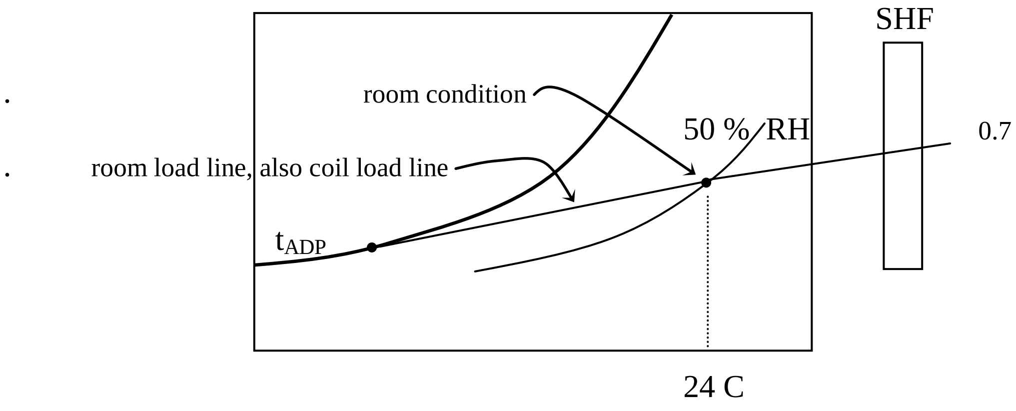
(i) supply air condition
(ii) supply air mass flow rate
(iii) ADP
(iv) The cooling and heating load on the coil

7.2.1 Simple recirculated system

(a) Only cooling coil (ie without reheat and no bypass)



$$\text{SHF} = \frac{Q_S}{Q_S + Q_L} = \frac{16}{16+7} = 0.7$$



(i) t_{SA} = 7.8 C (saturated)

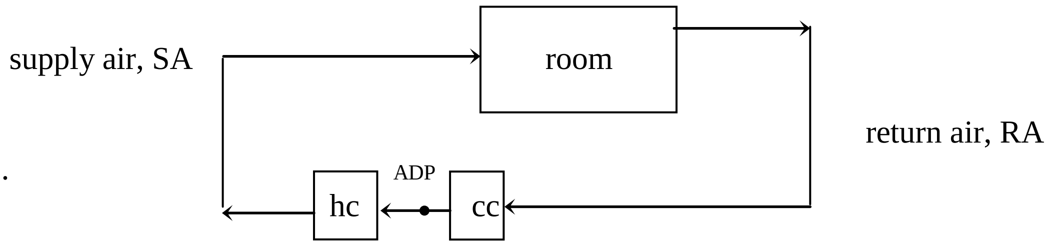
(ii) $$m_{SA} = \frac{Q_S}{c_{pm}\left(t_{RM} - t_{SA}\right)} = \frac{16}{1.02(24-7.8)} = 0.968 \text{ kg/s}$$

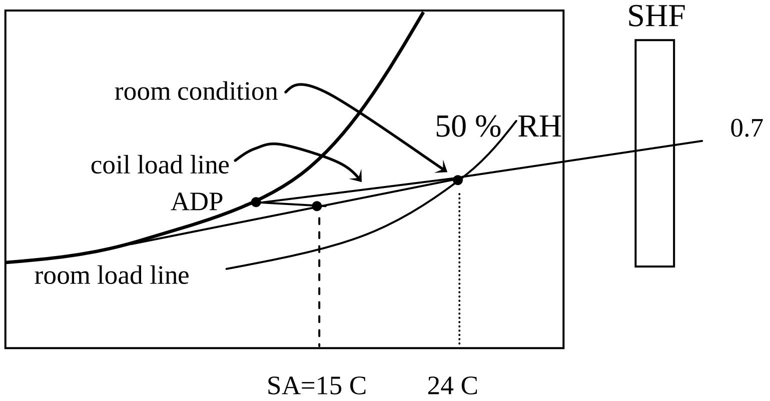
(iii) t_{ADP} = 7.8 C (which is also the supply air temp.)

(iv) Q_{REF} = 16 + 7 = 23 kW = m_a (h_{RA} – h_{SA})

Suppose that the <u>minimum supply air temperature</u> is 15 °C, then

(b) <u>With reheat</u>





(i) t_{SA} = 15 C, 72 % RH (read from chart)

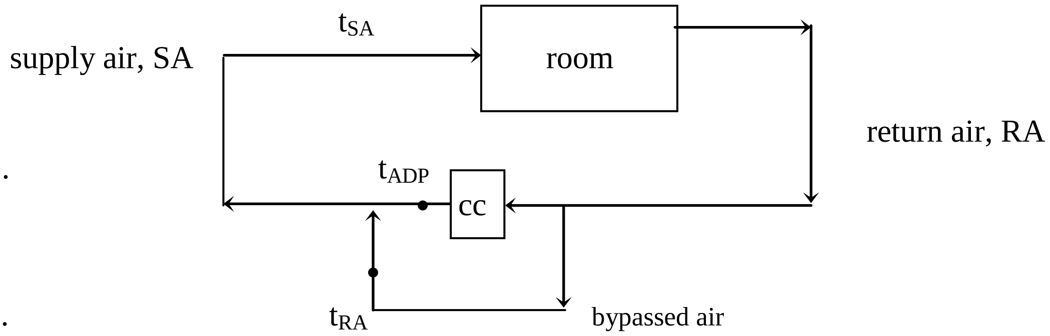
(ii) $$m_{SA} = \frac{Q_S}{c_{pm}\left(t_{RM} - t_{SA}\right)} = \frac{16}{1.02(24-15)} = 1.74 \text{ kg/s}$$

(iii) t_{ADP} = 10 C (from chart)

(iv) Q_{REF} = m_{SA} (h_{RA} – has) = 1.74 (48 – 29) = 33 kW

$Q_{HEATING}$ = m_{SA} (h_{SA} – h_{ADP}) = 1.74 (34 – 29) = 8.7 kW

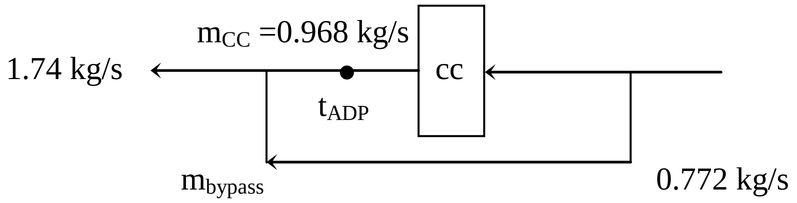
<u>(c) With bypassed air</u>



(i) supply air as before, 15 C dry bulb, 72 % RH
(ii) t_{ADP} = 7.8 C
(iii) m_{SA} = 1.74 kg/s (as before)

air quantity going through coil, m_{CC} = ?

$$m_{CC} = \frac{Q_S}{1.02(t_{RA} - t_{SA})} = \frac{16}{1.02(24 - 7.8)} = 0.968 \text{ kg/s}$$

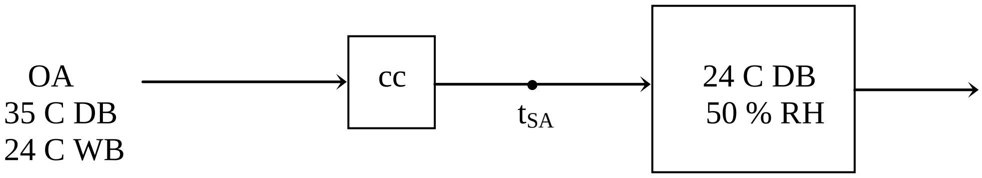


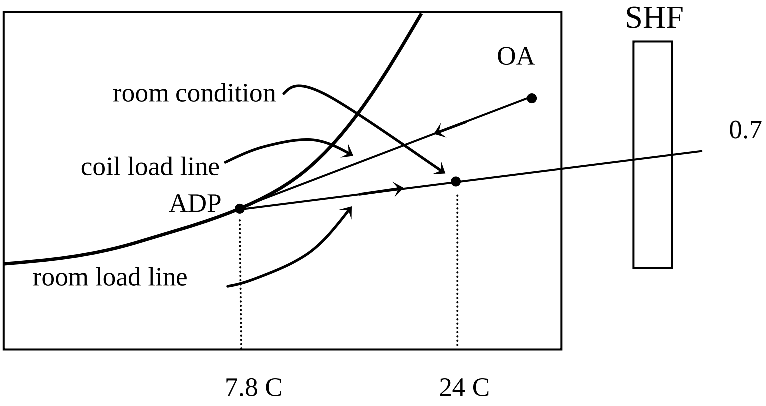
(iv) $Q_{REF} = m_{CC} (h_{RA} – h_{ADP})$ = 23 kW ?

7.2.2 All outside air system

Assume outside air condition: 35 C dry bulb, 24 C wet bulb

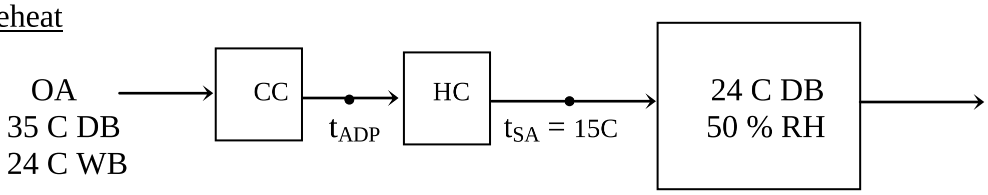
(a) Only cooling coil

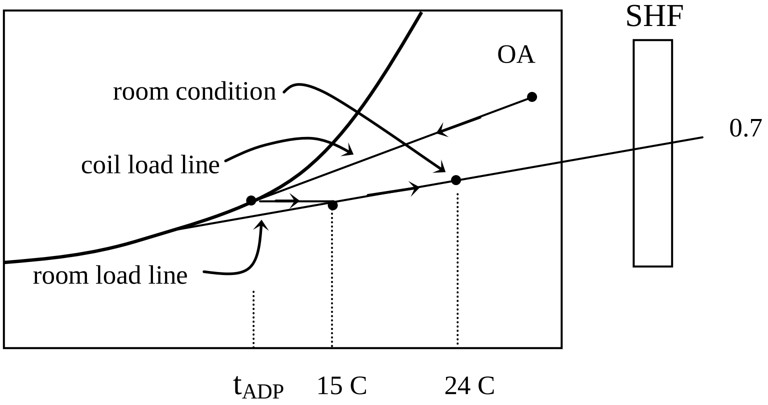




(i) t_{SA} = 7.8 C (saturated @ 100 % RH)
(ii) supply air mass flow rate, m_{SA} = 0.968 kg/s
(iii) apparaus dew point temperature, t_{ADP} = 7.8 C
(iv) refrigeration load, $Q_{REF} = m_{SA} (h_{OA} – h_{ADP})$ = 0.968(71.8 – 24) = 46.5 kW

(b) With Reheat



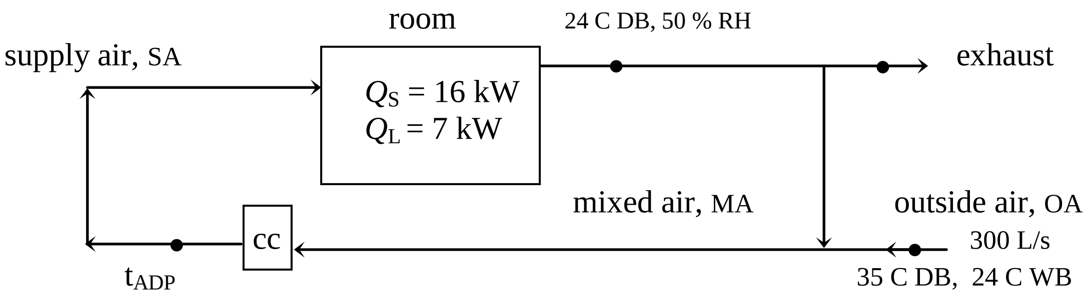


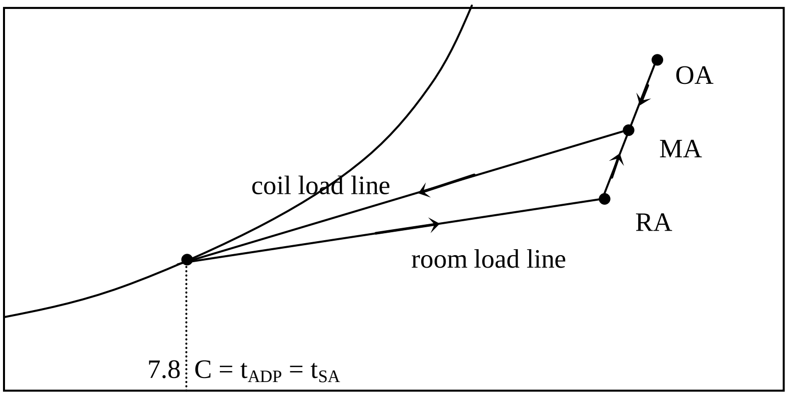
(i) supply air temp, t_{SA} = 15 C, 72 % RH
(ii) supply air mass flow rate, m_{SA} = 1.74 kg/s
(iii) apparatus dew point temperature, t_{ADP} = 10 C
(iv) refrigeration load, $Q_{REF} = m_{SA} (h_{OA} – h_{ADP})$ = 1.74(71.8 – 29) = 74.5 kW
(v) reheat rate, $Q_{REHEAT} = m_{SA} (h_{SA} – h_{ADP})$ = 10 kW

7.2.3 Recirculated and outside air systems (ie. REAL systems)

- Assume inside at 24 C DB, 50 % RH
- Outside 35 C DB, 24 C WB
- Ventilation requirement (fresh air): 300 L/s

(a) Only cooling coil





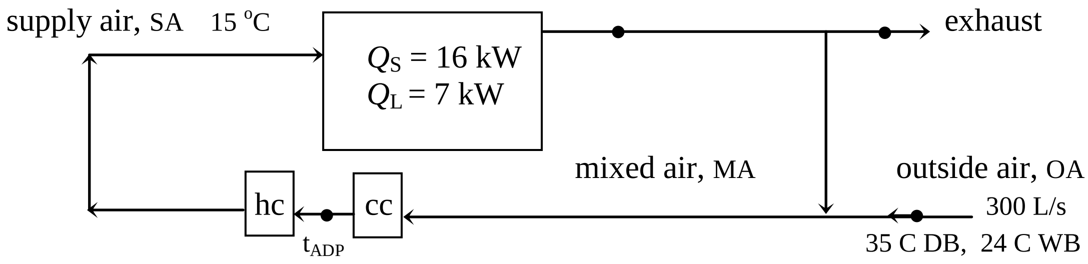
Using $m = \frac{V}{v}$, for outside air, $m_{OA} = \dfrac{0.3\frac{m^3}{s}}{0.893\frac{m^3}{kg_{DA}}}$ = 0.336 kg/s

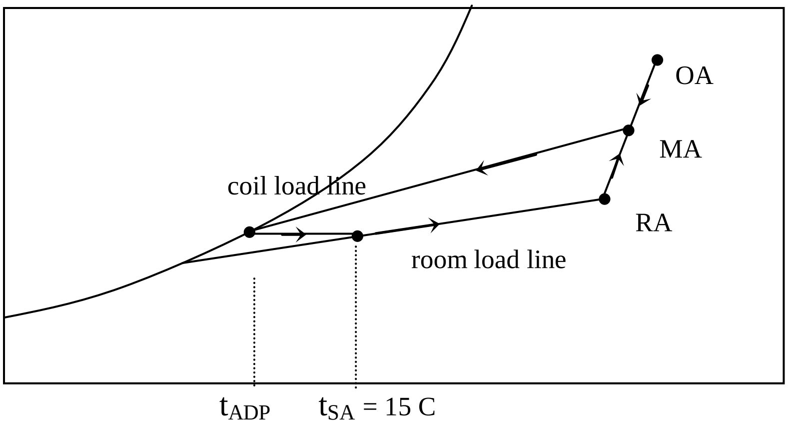
$m_{SA} = \dfrac{Q_S}{1.02(t_{RM} - t_{SA})} = \dfrac{16}{1.02(24-7.8)}$ = 0.968 kg/s

$\dfrac{m_{OA}}{m_{SA}} = \dfrac{0.336}{0.968}$ = 0.347

(i) supply air condition, t_{SA} = 7.8 C (saturated)
(ii) m_{SA} = 0.968 kg/s
(iii) t_{ADP} = 7.8 C
(iv) $Q_{REF} = m_{SA}\,(h_{MA} - h_{ADP})$ = 0.968 (55.5 – 24) = 30 kW

<u>(b) With reheat</u> (minimum supply air temp = 15 C)





supply air mass flow rate, $m_{SA} = \dfrac{Q_S}{c_{pm}(t_{RM} - t_{SA})} = \dfrac{16}{1.02(24-15)}$ = 1.74 kg/s

$\dfrac{m_{OA}}{m_{SA}} = \dfrac{0.336}{1.74}$ = 0.193

(i) t_{SA} = 15 °C, 72 % RH
(ii) m_{SA} = 1.74 kg/s
(iii) t_{ADP} = 10 °C
(iv) $Q_{REF} = m_{SA}\,(h_{MA} - h_{ADP})$ = 1.74 (52 – 29) = 40 kW