02/02/2021

0.1 Psychrometric Chart

0.1.1 Air-Water Vapour Properties

How to evaluate air-water vapour properties?

- Psychrometric relationships
- Psychrometric chart
- Computer programme/database

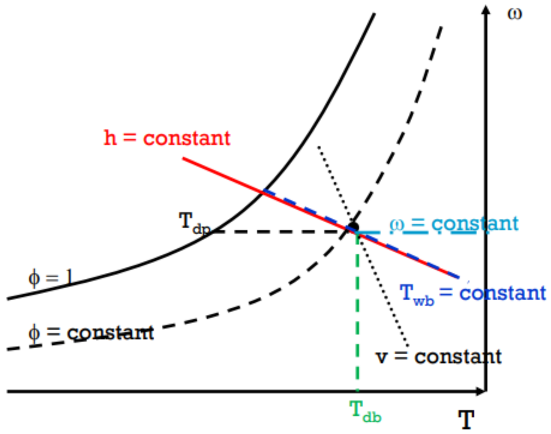

Figure 1:

Psychrometric Chart:

- Graphical relationship between: T_{db}, T_{wb}, T_{dp}, ω, ϕ, h, v
- Constructed for pressure at 1 bar
- Valid for mixture pressure around 1 bar, for engineering analysis
- Useful for visualizing air-water vapour processes at constant pressure
- The specific volume ($v = V/m_a$) has the unit of $\mathrm{m^3\,kg^{-1}}$ dry air
- h gives the mixture enthalpy per unit mass of dry air in the mixture:

$$h = \frac{H}{m_a} = h_a + \omega h_v \ (\mathrm{kJ\,kg^{-1}}\ \text{dry air}) \tag{0.1.1}$$

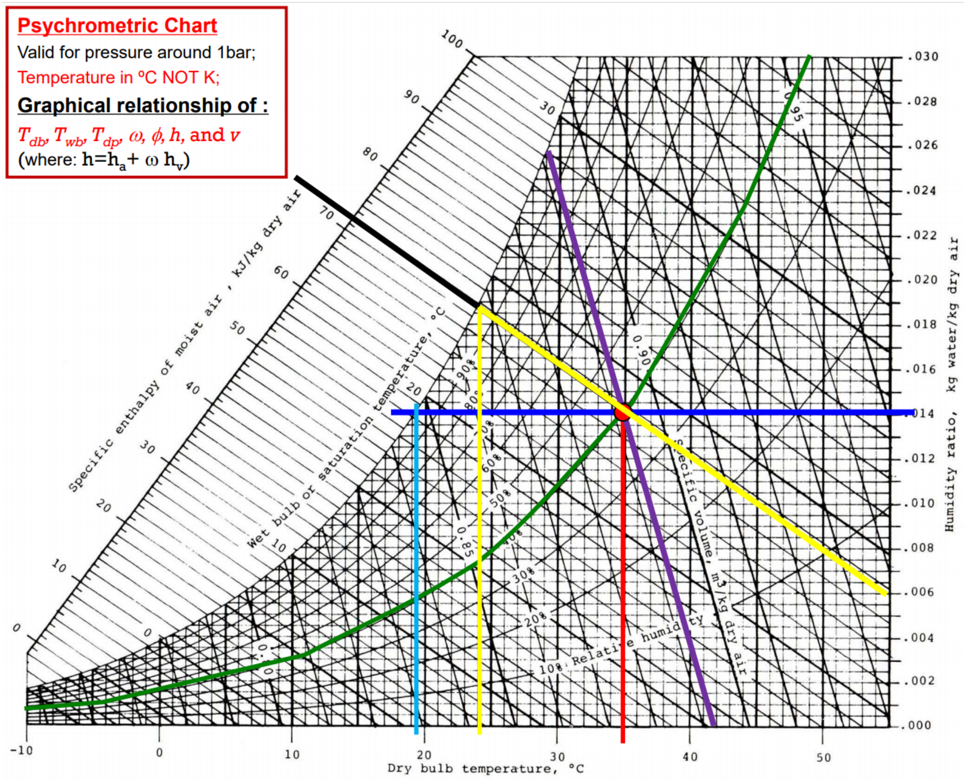

Figure 2:

0.2 Psychrometric Applications

0.2.1 Summer and Winter Comfort Zones

Comfort zones: Acceptable ranges of operative temperature and humidity for people in typical summer and winter clothing during primarily sedentary activity.

Air-conditioning: To change the temperature and water vapour fraction in the moist air

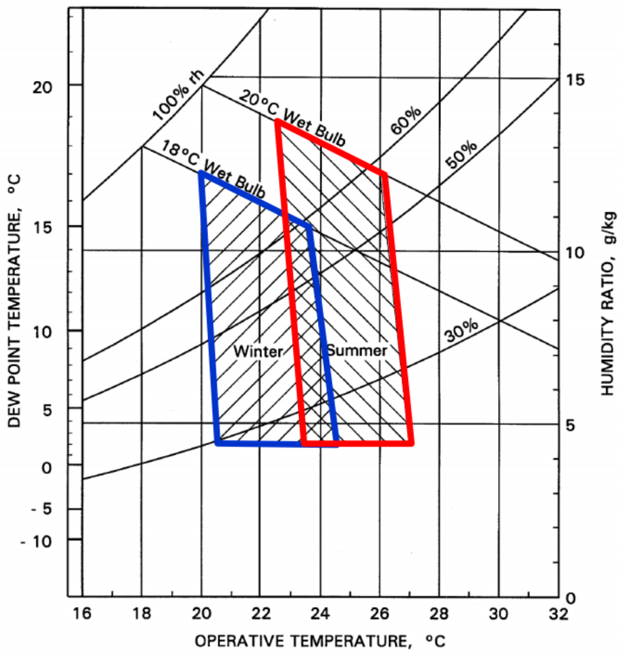

Figure 3:

0.2.2 List of Psychrometric Applications

- Cooling with and without Dehumidification
- Cooling with Dehumidification and Reheating
- Evaporative Cooling
- Humidification
- Humidification with Heating
- Adiabatic Mixing
- Cooling Tower

The first 5 of these applications are known of **Refrigerant, Air-Conditioning Processes**.

0.2.3 Air-Conditioning Processes

- Simple Heating and Cooling (ω=constant), no change in the amount of water vapour.
- Cooling with Dehumidification
- Heating with Humidification

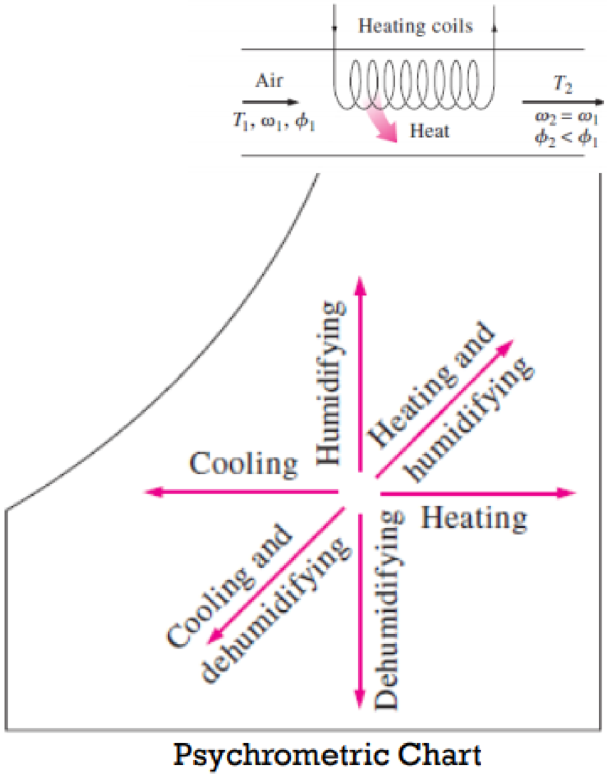

Figure 4:

Mass and Energy Balance for Open Systems:

Mass balance for multiple inlets and exits:

$$\frac{\mathrm{d}m_{cv}}{\mathrm{d}t} = \sum_i \dot{m}_i - \sum_e \dot{m}_e \tag{0.2.1}$$

Energy balance for multiple inlets and exits:

$$\frac{\mathrm{d}E_{cv}}{\mathrm{d}t} = \dot{Q}_{cv} + \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{V_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left(h_e + \frac{V_e^2}{2} + gz_e \right) \tag{0.2.2}$$

Steady state:

$$\frac{\mathrm{d}m_{cv}}{\mathrm{d}t} = 0 \tag{0.2.3}$$

$$\frac{\mathrm{d}E_{cv}}{\mathrm{d}t} = 0 \tag{0.2.4}$$

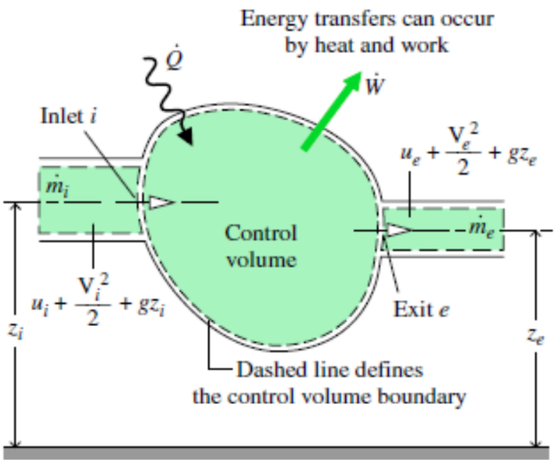

Figure 5:

Air-Conditioning Processes:

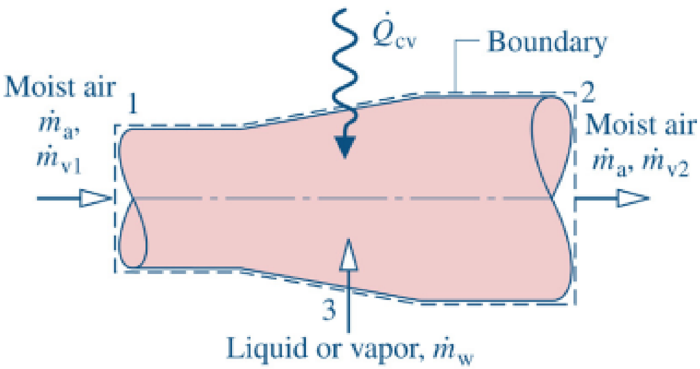

Figure 6:

- On control volume basis;
- Steady State;
- Assume
  - $W_{cv} = 0$
  - $\Delta KE = 0$
  - $\Delta PE = 0$
- Heat transfer between the control volume and its surroundings;
- Liquid water (mist) or vapour added

Mass Balance:

$$\dot{m}_{a1} = \dot{m}_{a2} = \dot{m}_a \qquad \text{(dry air)} \tag{0.2.5}$$

$$\dot{m}_{v1} + \dot{m}_w = \dot{m}_{v2} \qquad \text{(water)} \tag{0.2.6}$$

$$\dot{m}_{v1} = \omega_1 \dot{m}_a \quad \text{and} \quad \dot{m}_{v2} = \omega_2 \dot{m}_a \tag{0.2.7}$$

$$\therefore \dot{m}_w = \dot{m}_a(\omega_2 - \omega_1) \qquad \text{(water)} \tag{0.2.8}$$

Energy Balance:

$$0 = \dot{Q}_{cv} + (\dot{m}_a h_{a1} + \dot{m}_{v1} h_{v1}) + \dot{m}_w h_w - (\dot{m}_a h_{a2} + \dot{m}_{v2} h_{v2}) \tag{0.2.9}$$

$$0 = \dot{Q}_{cv} + \dot{m}_a \left[(h_{a1} + \omega_1 h_{v1}) + (\omega_2 - \omega_1) h_w - (h_{a2} + \omega_2 h_{v2}) \right] \tag{0.2.10}$$

$$0 = \dot{Q}_{cv} + \dot{m}_a [h_1 + (\omega_2 - \omega_1) h_w - h_2] \tag{0.2.11}$$

The $(h_{a1} + \omega_1 h_{v1})$ term represents the **total specific enthalpy of the mixture** at Point 1, and the $(h_{a2} + \omega_2 h_{v2})$ term represents the **total specific enthalpy of the mixture** at Point 2. They can be simplified by writing in h_1 and h_2 respectively. The quantities h_1 and h_2 can be obtained from the Psychrometric Chart, while the entropy of water, h_w, can be obtained from the Property Tables.

Alternatively, enthalpies of the water vapour can be treated as the saturated vapour enthalpies at the corresponding temperatures:

$$h_{v1} \approx h_{g1} \tag{0.2.12}$$

$$0 = \dot{Q}_{cv} + \dot{m}_a \left[(h_{a1} - h_{a2}) + \omega_1 h_{g1} + (\omega_2 - \omega_1) h_w - \omega_2 h_{g2} \right] \tag{0.2.13}$$

All the properties above can be found from the relevant tables:

- $(h_{a1} - h_{a2}) \longrightarrow$ Dry Air: Table A-22 — OR: $h_2 - h_1 = c_p(T_2 - T_1)$
- $\omega_1 h_{g1} + (\omega_2 - \omega_1) h_w - \omega_2 h_{g2} \longrightarrow$ Steam Table

0.2.4 Cooling with and without Dehumidification

Refrigeration:

- During the evaporation of the refrigerant, heat is absorbed from an air stream
- Air side process = cooling process with or without dehumidification
- Dehumidification occurs only if air stream temperature drops below dew point temperature
- Otherwise, air side process = cooling process at constant humidity ratio

Analysis:

- **Dry coil analysis:** no dehumidification, air stream temperature stays above dew point temperature of incoming air stream
- **Wet coil analysis:** dehumidification, air stream temperature drops below dew point temperature of incoming air stream

Cooling without Dehumidification

Cooling Process, Dry Coil Analysis:

Assumptions:

- $\Delta KE = \Delta PE = 0$
- Steady state

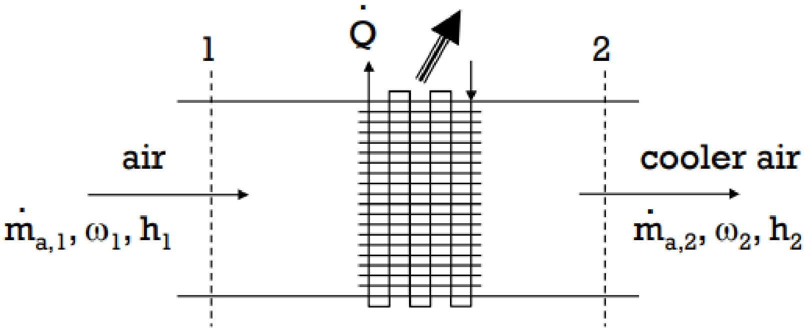

Figure 7:

$$\text{Dry air mass balance:} \quad \dot{m}_{a,1} = \dot{m}_{a,2} = \dot{m}_a \tag{0.2.14}$$

$$\text{Water mass balance:} \quad \dot{m}_a \omega_1 = \dot{m}_a \omega_2 \tag{0.2.15}$$

$$\text{Energy balance:} \quad \dot{Q} = \dot{m}_a (h_2 - h_1) \tag{0.2.16}$$

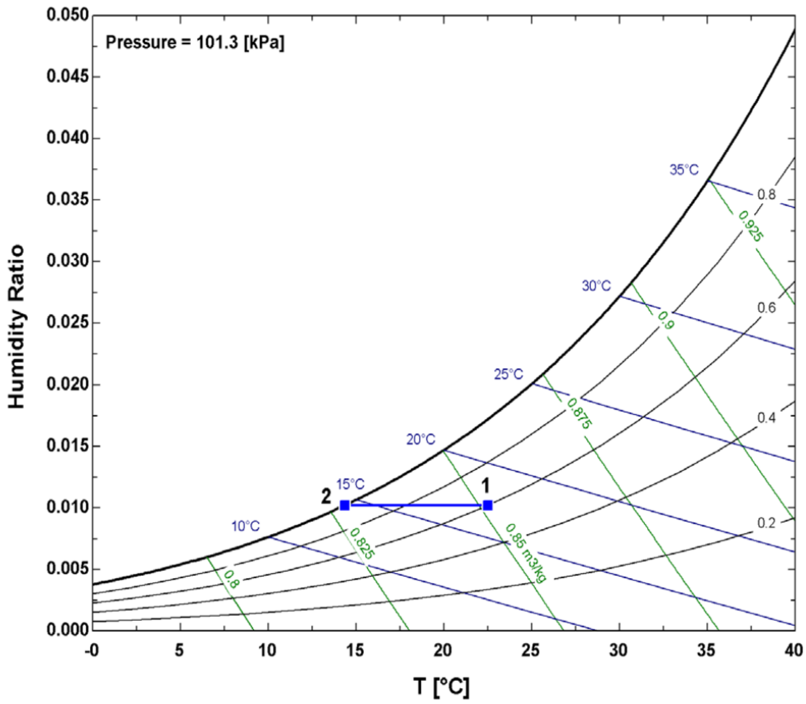

Figure 8:

Cooling with Dehumidification

Cooling Process, Wet Coil Analysis:

Assumptions:

- $\Delta KE = \Delta PE = 0$
- Steady state

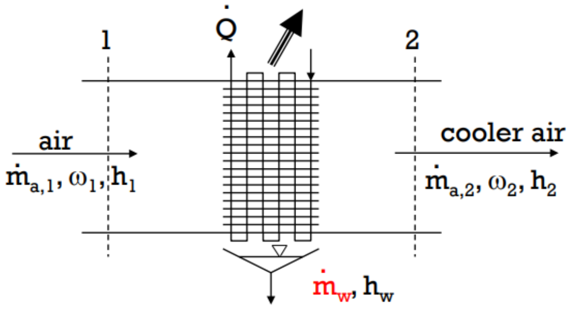

Figure 9:

$$\text{Dry air mass balance:} \quad \dot{m}_{a,1} = \dot{m}_{a,2} = \dot{m}_a \tag{0.2.17}$$

$$\text{Water mass balance:} \quad \dot{m}_a \omega_1 = \dot{m}_a \omega_2 + \dot{m}_w \tag{0.2.18}$$

$$\longrightarrow \quad \dot{m}_w = \dot{m}_a(\omega_1 - \omega_2) \tag{0.2.19}$$

$$\text{Energy balance:} \quad \dot{Q} = \dot{m}_a(h_2 - h_1) + \dot{m}_w h_w \tag{0.2.20}$$

$$= \dot{m}_a \left[(h_2 - h_1) + (\omega_1 - \omega_2)h_w\right] \tag{0.2.21}$$

Note - Outlet state is saturated: $\phi_2 = 1.0$

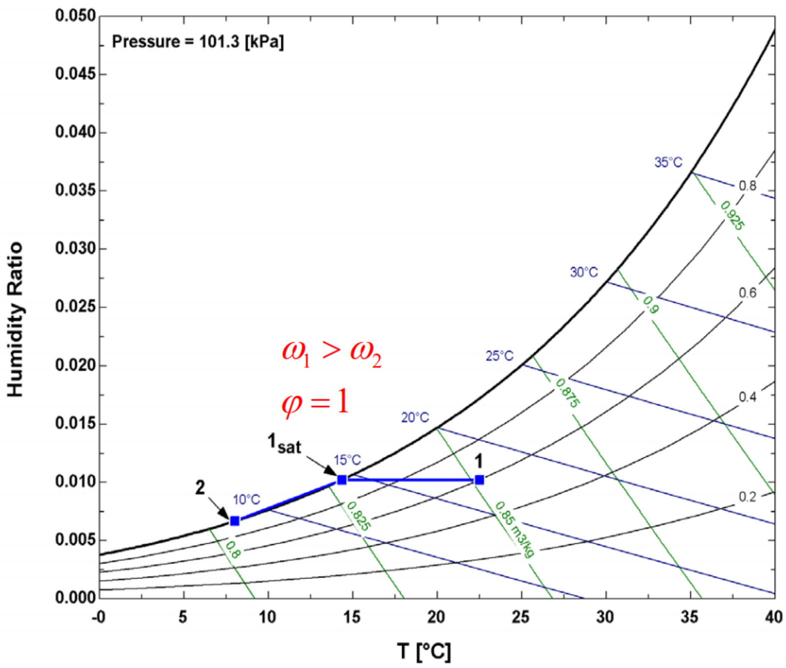

Figure 10:

Real air coil with dehumidification:

- Bulk air stream temperature between two fins may not reach dew point temperature $\longrightarrow$ no dehumidification
- Air stream temperature close to the fin surface drops below dew point temperature $\longrightarrow$ dehumidification
- Combined air stream leaving the coil may not be saturated!

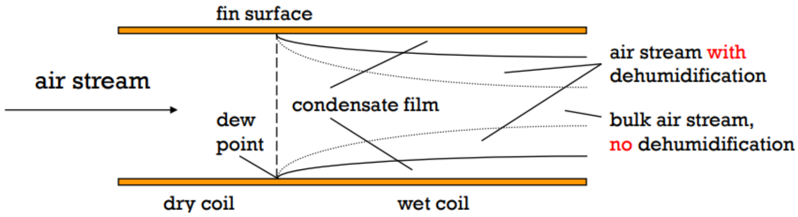

Figure 11:

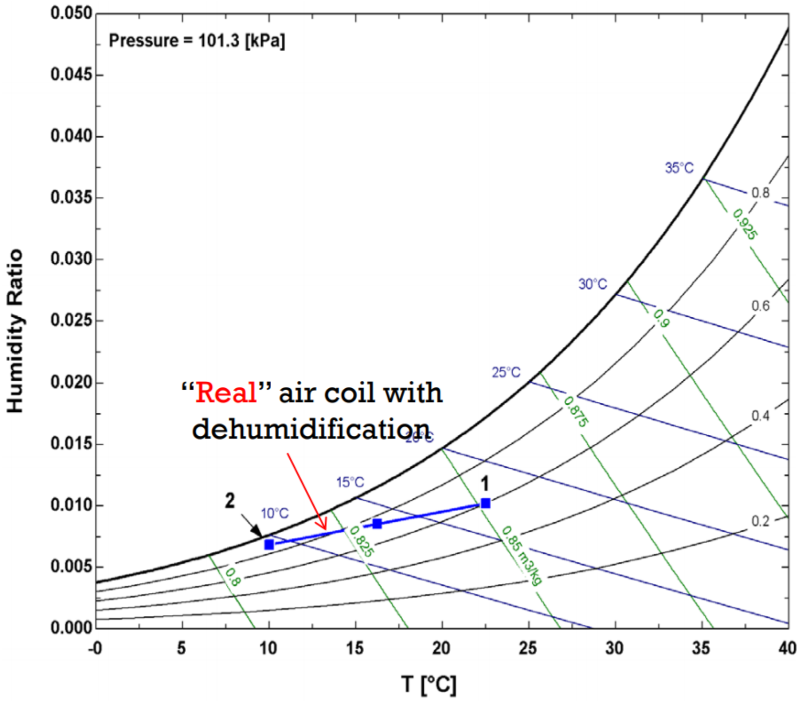

Figure 12:

0.2.5 Humidification

Difference with respect to evaporative cooling (Use water vapour (steam) instead of liquid water to humidify the air)

Assumptions:

- $\Delta KE = \Delta PE = 0$
- Steady state
- $p =$ constant

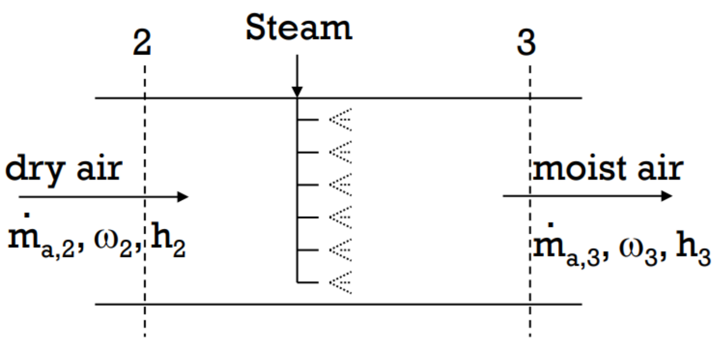

Figure 13:

Mass Balances:

$$\dot{m}_{a,2} = \dot{m}_{a,3} = \dot{m}_a \qquad \text{(dry air)} \tag{0.2.22}$$

$$\dot{m}_w = \dot{m}_a(\omega_3 - \omega_2) \qquad \text{(water)} \tag{0.2.23}$$

Energy Balance:

$$h_3 = h_2 + (\omega_3 - \omega_2)h_{st} \tag{0.2.24}$$

For Steam Humidification:

$$h_{st} = h_{vapour}(T_{st}; p_{st}) \longrightarrow T_3 > T_2 \tag{0.2.25}$$

For Evaporative Cooler:

$$h_{st} = h_w = h_f(T_3) \longrightarrow T_3 < T_2 \tag{0.2.26}$$

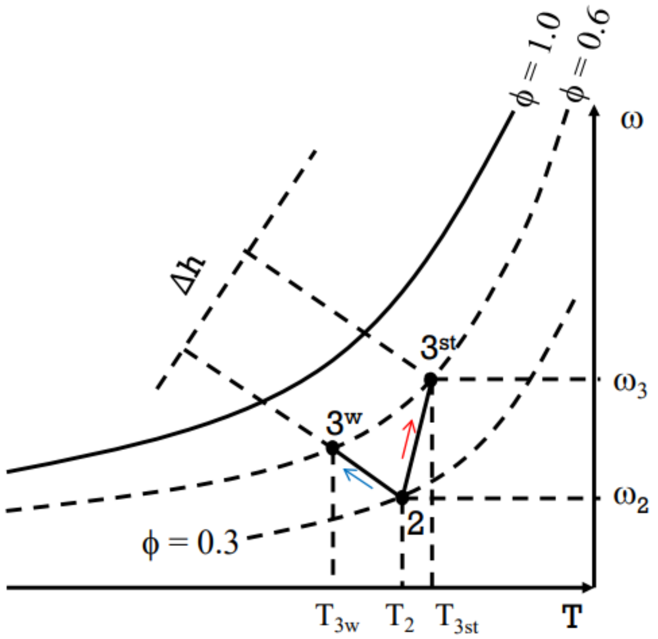

Figure 14:

0.2.6 Humidification with Heating

During winter time, when the outdoor humidity is low, typically **both** heating and humidification are needed in door.

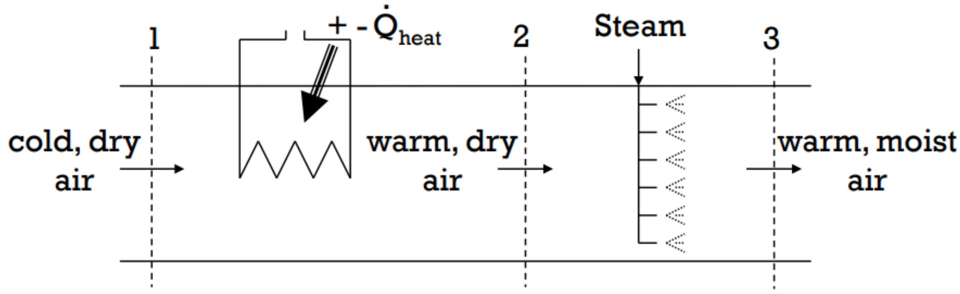

Figure 15:

Heating Coil:

- Hot water
- Steam
- Combustion gases
- Electric heater

Dry air mass balance:

$$\dot{m}_{a,1} = \dot{m}_{a,2} = \dot{m}_{a,3} = \dot{m} \tag{0.2.27}$$

Water mass balance:

$$\omega_1 \dot{m}_a = \omega_2 \dot{m}_a \longrightarrow \omega_1 = \omega_2 \tag{0.2.28}$$

$$\omega_2 \dot{m}_a + \dot{m}_{st} = \omega_3 \dot{m}_a \longrightarrow \dot{m}_{st} = \dot{m}_a(\omega_3 - \omega_2) \tag{0.2.29}$$

Energy balance on heater:

$$\dot{Q}_{heat} = \dot{m}_a(h_2 - h_1) \tag{0.2.30}$$

Energy balance on humidification:

$$h_3 = h_2 + (\omega_3 - \omega_2)h_{st} \tag{0.2.31}$$

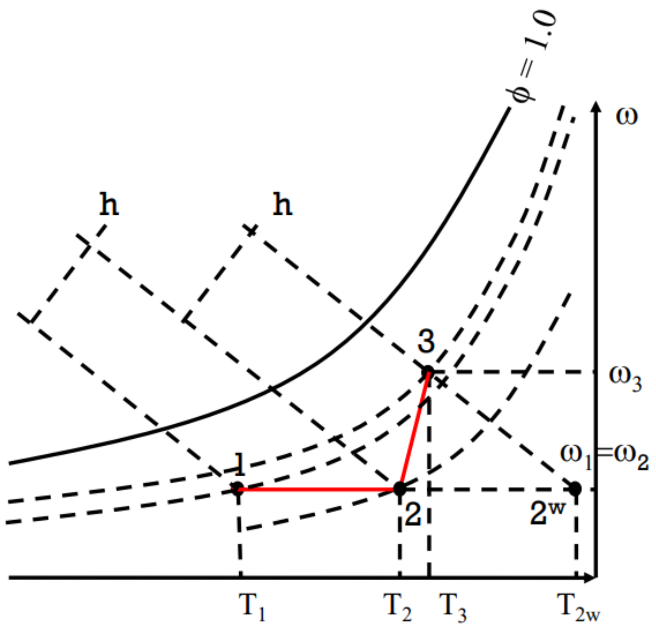

Figure 16:

0.2.7 Evaporative Cooling

Used in desert climates, where it is hot and dry (low relative humidity).

Analysis is just like **adiabatic saturator** analysis, except that the supply water temperature is independent of saturation temperature.

Assumptions:

- $\Delta KE = \Delta PE = 0$
- Steady state
- $p =$ constant

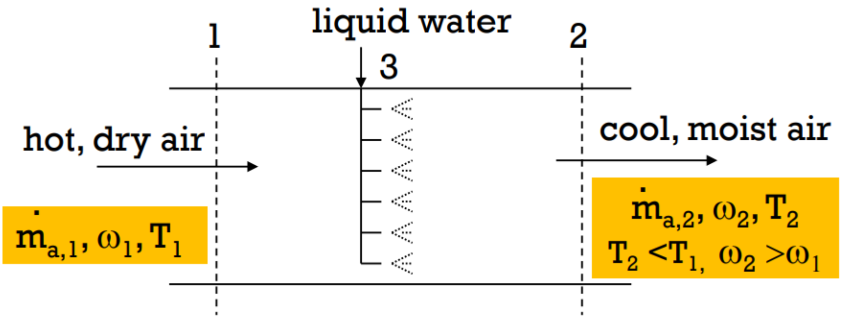

Figure 17:

Mass Balances:

$$\dot{m}_{a,1} = \dot{m}_{a,2} = \dot{m}_a \qquad \text{(dry air)} \tag{0.2.32}$$

$$\dot{m}_w = \dot{m}_a(\omega_2 - \omega_1) \qquad \text{(water)} \tag{0.2.33}$$

Energy Balance:

$$(h_{a2} + \omega_2 h_{v2}) = (h_{a1} + \omega_1 h_{v1}) + (\omega_2 - \omega_1)h_f \tag{0.2.34}$$

$$h_2 = h_1 + (\omega_2 - \omega_1)h_f \tag{0.2.35}$$

The $(\omega_2 - \omega_1)h_f$ term is much smaller than the other two terms:

$$\therefore h_2 \approx h_1 \quad \text{is a good approximation} \tag{0.2.36}$$

$$\therefore h \approx \text{constant} \quad \& \quad T_{wb} \approx \text{constant} \tag{0.2.37}$$

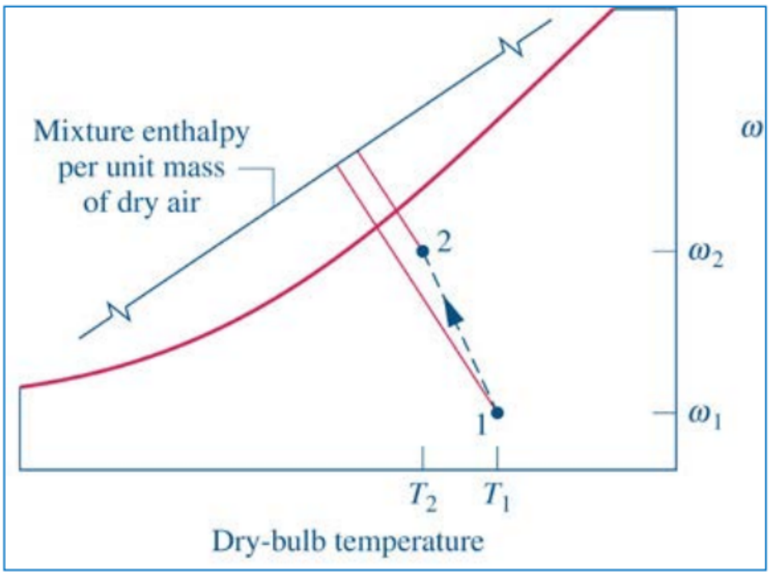

Figure 18:

0.2.8 Adiabatic Mixing of Two Moist Air Streams

Adiabatic Mixing of state 1 and state 2:

- Assume:
  - $\dot{Q} = 0$
  - $\dot{W} = 0$
- Mixing state is **on a straight line** between the two inlet state points

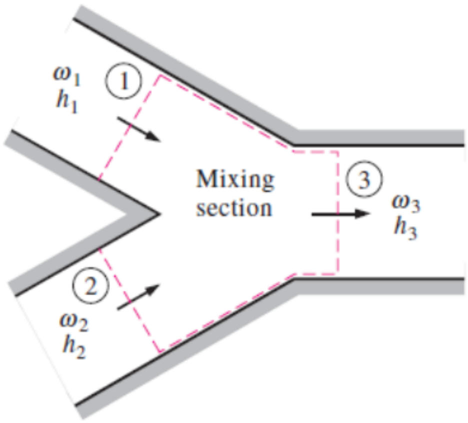

Figure 19:

Dry air mass balance:

$$\dot{m}_{a,3} = \dot{m}_{a,1} + \dot{m}_{a,2} \tag{0.2.38}$$

Vapour mass balance:

$$\omega_3 \dot{m}_{a,3} = \omega_1 \dot{m}_{a,1} + \omega_2 \dot{m}_{a,2} \tag{0.2.39}$$

Energy balance:

$$h_3 \dot{m}_{a,3} = h_1 \dot{m}_{a,1} + h_2 \dot{m}_{a,2} \tag{0.2.40}$$

$$\frac{\dot{m}_{a1}}{\dot{m}_{a2}} = \frac{\omega_2 - \omega_3}{\omega_3 - \omega_1} = \frac{h_2 - h_3}{h_3 - h_1} \tag{0.2.41}$$

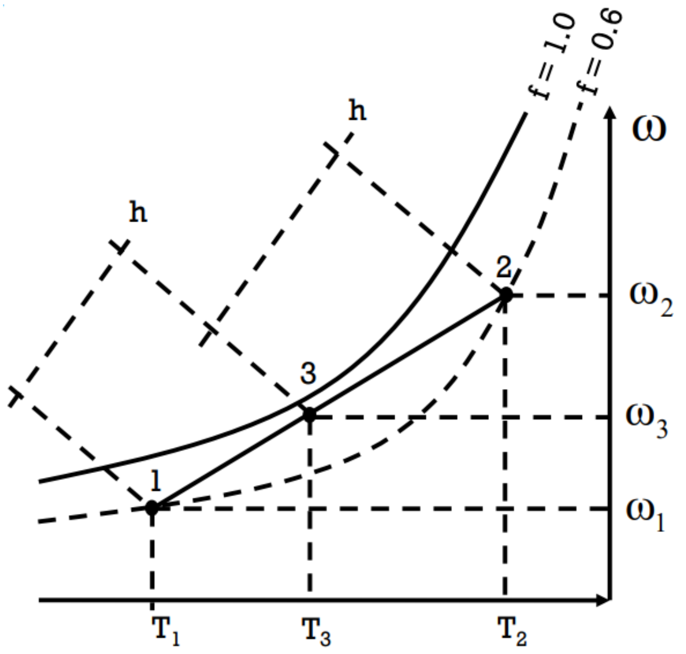

Figure 20:

0.2.9 Cooling Towers

- Cooling towers are used to:
  1. Release power plant waste heat at acceptable T to surroundings
  2. Provide chilled water
- Operate by natural or forced convection of air
- Counterflow, cross flow or hybrid configuration

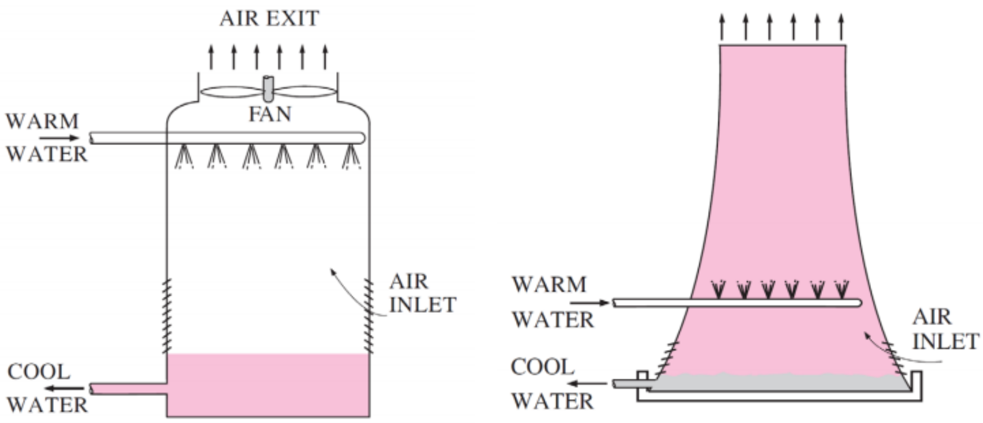

Figure 21: Left: An induced-draft counterflow cooling tower — Right: A natural-draft cooling tower

- Steady state analysis of mass and energy balance, usually;
- Heat transfer to surroundings is neglected, usually.
- Fan power may be considered

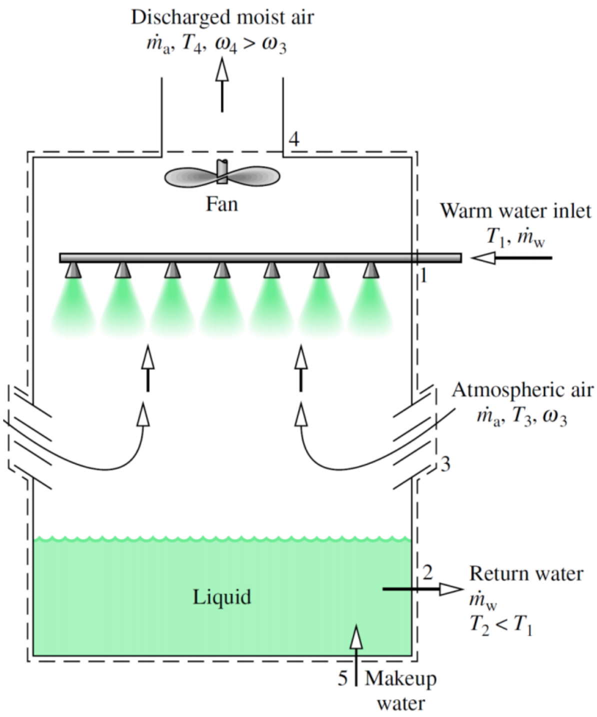
Discharged moist air
$\dot{m}_a$, T_4, $\omega_4 > \omega_3$
4
Fan
Warm water inlet
T_1, $\dot{m}_w$
1
Atmospheric air
$\dot{m}_a$, T_3, ω_3
3
Liquid
2
Return water
$\dot{m}_w$
$T_2 < T_1$
5
Makeup
water

Figure 22: