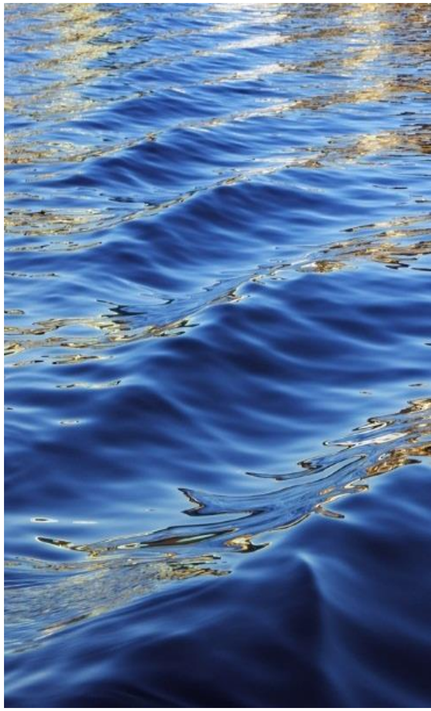
Environmental Thermal Engineering

Lecture Note #10

Professor Min Soo KIM

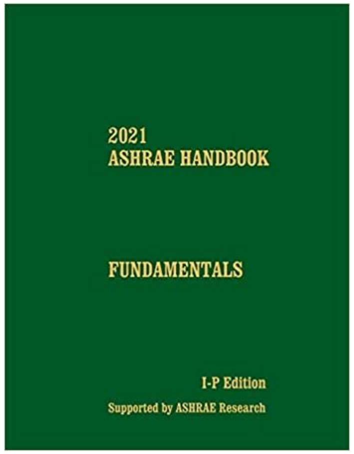


Air-conditioning

What is Air-conditioning?

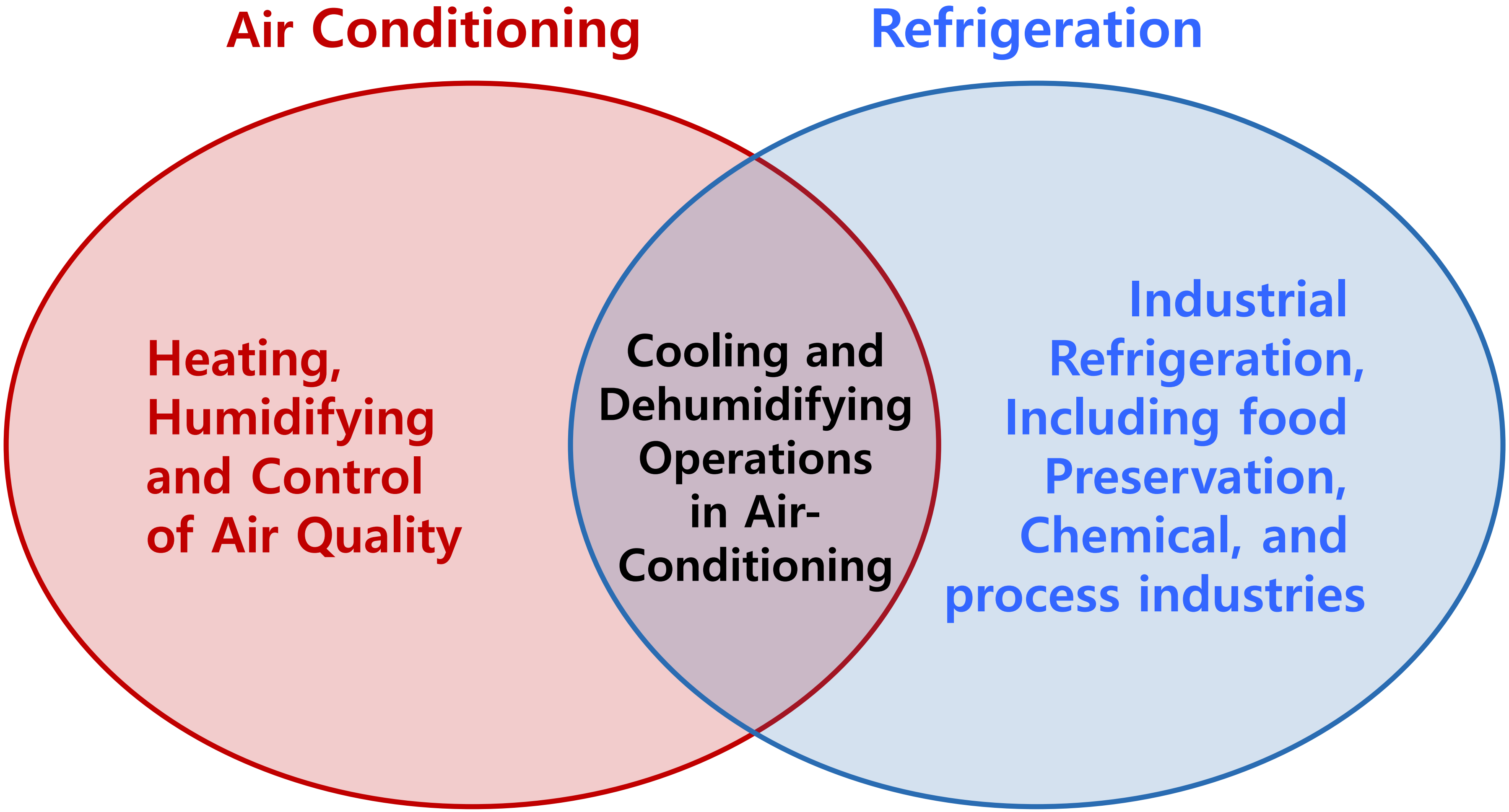
- The process of treating air to control simultaneously its **temperature**, **humidity**, **cleanliness** and **distribution** to meet the comfort requirements of the occupants of the conditioned space

(“ASHRAE Handbook, Fundamentals, ” American Society of Heating, Refrigerating and Air-Conditioning Engineers)



Air-conditioning

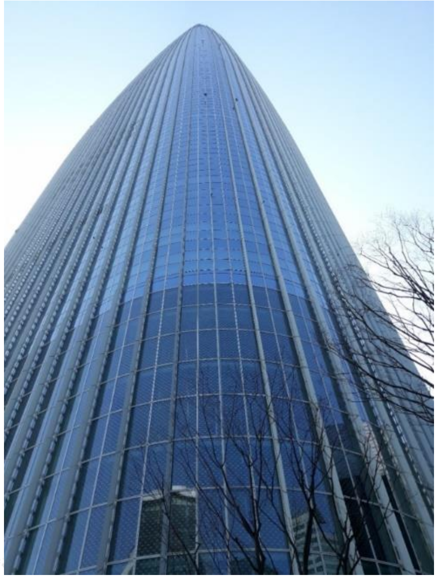
❑ **Relationship of the refrigeration and air-conditioning fields**



Air-conditioning

HVAC & R

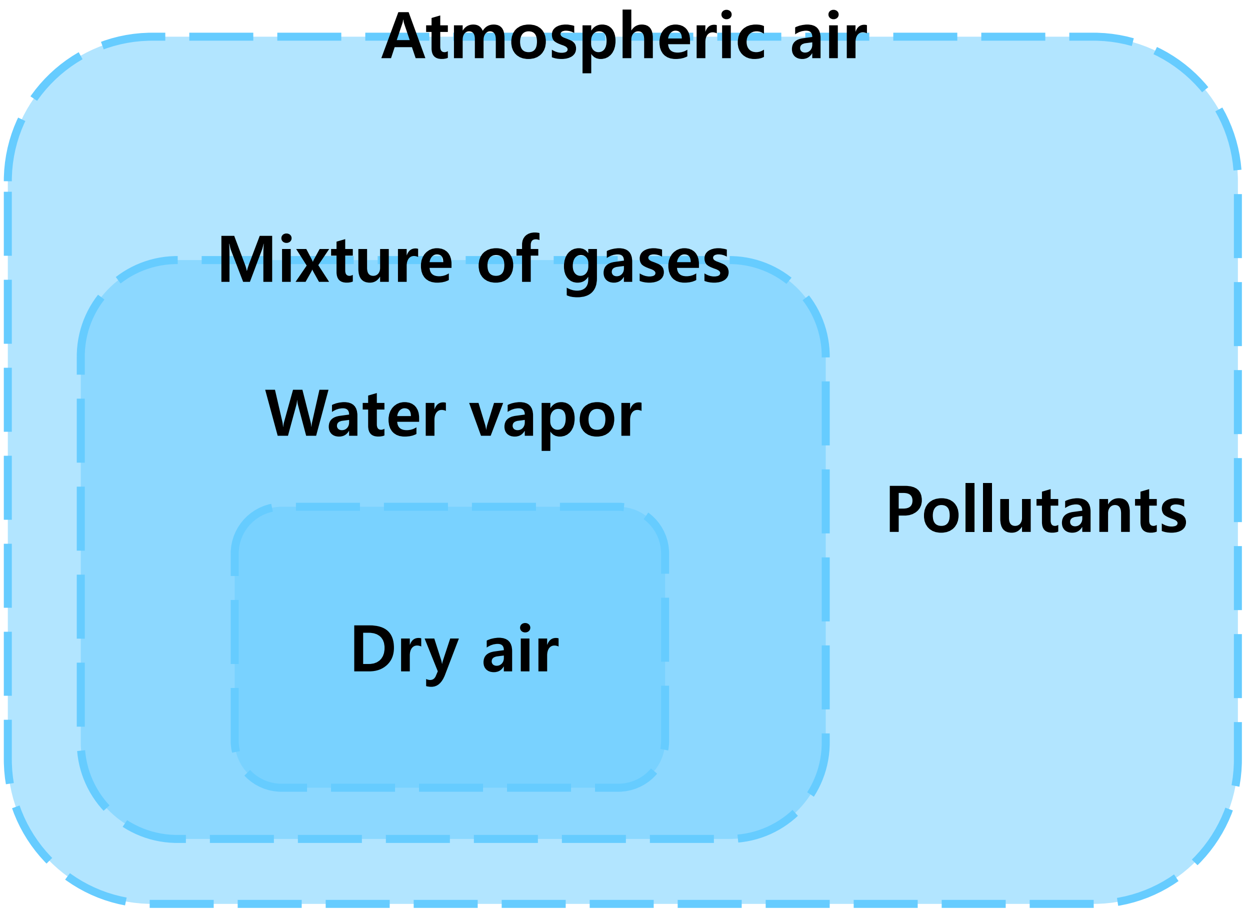
- **H**eating
- **V**entilating
- **A**ir **C**onditioning
- **R**efrigeration



Ref. www.lwt.co.kr

Moist Air Properties and Conditioning Processes

Moist Air and the Standard Atmosphere



Moist Air and the Standard Atmosphere

- **Dry air : treated as a mixed gas containing nitrogen (78%), oxygen (21%), and argon (1%).**
- **Wet air: When dry air contains water vapor,**
- **In atmospheric conditions, the mass of 1 m3 of air is about 1.3 kg, of which 0.015 kg or more of water vapor is contained.**
- **When dealing with wet air, dry air is treated as pure gas.**
- **If the pressure is not particularly high, wet air is treated as an ideal gas.**

TABLE Composition of dry air

Constituent	Molecular mass	Volume fraction
Oxygen	32.000	0.2095
Nitrogen	28.016	0.7809
Argon	39.944	0.0093
Carbon Dioxide	44.010	0.0003

Moist Air and the Standard Atmosphere

❑ Ideal gas relation

$$Pv = \frac{p}{\rho} = R_a T$$

❑ Gas constant

$$R_a = \frac{\bar{R}}{M_a} = \frac{1545.32}{28.965} = 53.352\,(\mathrm{ft}\cdot\mathrm{lbf})/(\mathrm{lbm}\cdot\mathrm{R}), \quad 287\,\mathrm{J}/(\mathrm{kg}\cdot\mathrm{K})$$ **air**

❑ Universal gas constant

$$\bar{R} = 1545.32(\mathrm{ft}\cdot\mathrm{lbf})/(\mathrm{lbm}\cdot\mathrm{R}), \quad 8314\,\mathrm{J}/(\mathrm{kg}\cdot\mathrm{K})$$

$$R_v = \frac{\bar{R}}{M_v} = \frac{1545.32}{18.015} = 85.78(\mathrm{ft}\cdot\mathrm{lbf})/(\mathrm{lbm}\cdot\mathrm{R}), \quad 462\,\mathrm{J}/(\mathrm{kg}\cdot\mathrm{K})$$ **vapor**

Moist Air and the Standard Atmosphere

❑ Assume ideal gases

Separately calculate dry air & water vapor and then add results

❑ Dalton's law

$$P = p_1 + p_2 + p_3 + \cdots$$

- for moist air

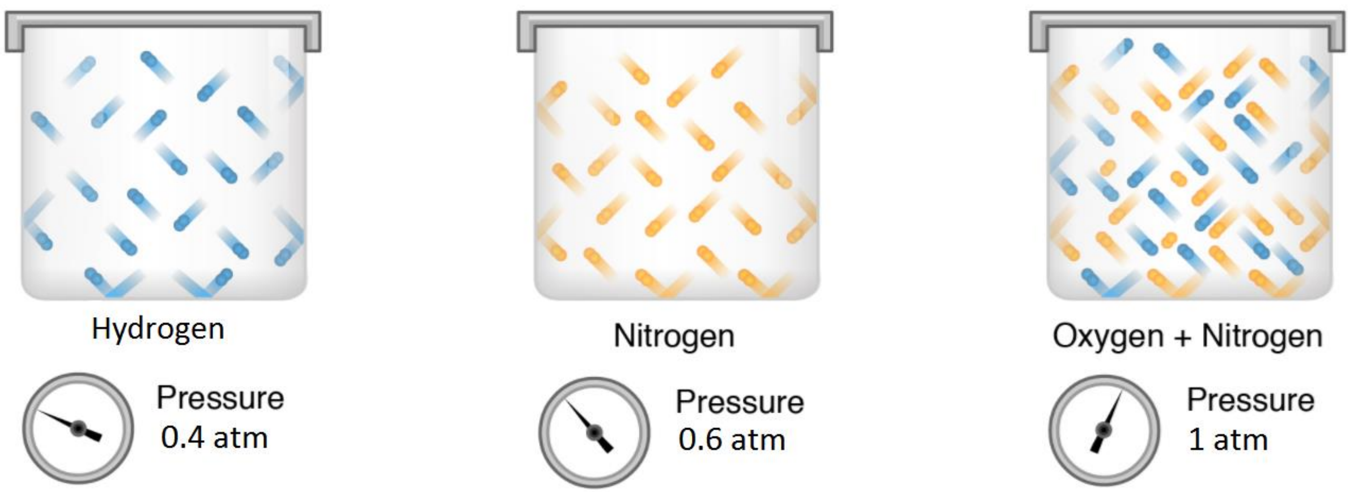
$$P = p_{N_2} + p_{O_2} + p_{CO_2} + p_A + p_v$$

$$P = p_a + p_v$$

Dalton's Law

- **Dalton's Law states** that the total pressure of a mixture of gases is equal to the sum of the partial pressures of each of the component gases.

$$P_{total} = P_1 + P_2 + P_3 + \ldots$$



Fundamental Parameters

1. **Saturated Line**

   - Moist air reached to the saturation state
   - Saturated vapor pressure

2. **Dew point temperature**

   - temp. of saturated moist air at the same pressure and humidity ratio

3. **Humidity ratio**

$$W = \frac{m_v}{m_a} = \frac{\text{mass of water vapor}}{\text{mass of dry air}}$$

Fundamental Parameters

4. Relative humidity (상대습도)

$$\phi = \frac{x_v}{x_a} = \frac{\text{mole fraction of water vapor}}{\text{mole fraction of water vapor for a saturated mixture}}$$

For ideal gas

$$x_v = \frac{p_v}{p_a + p_v} = \frac{p_v}{P}, \qquad \phi = \frac{p_v / P}{p_s / P} = \frac{p_v}{p_s}, \qquad \phi = \frac{\rho_v / R_v T}{\rho_s / R_v T} = \frac{\rho_v}{\rho_s}$$

5. Degree of saturation

$$\mu = \frac{W}{W_s}$$

Fundamental Parameters

6. A relation between w and ϕ .

$$m_v = \frac{p_v V}{R_v T} = \frac{p_v V M_v}{\bar{R} T}, \qquad m_a = \frac{p_a V}{R_a T} = \frac{p_a V M_a}{\bar{R} T}$$

Divide upper equations

$$w = \frac{M_v p_v}{M_a p_a}$$

$$w = \frac{18.015 p_v}{28.965 p_a} = 0.6219 \frac{p_v}{p_a} \qquad (\leftarrow \phi = \frac{p_v}{p_a})$$

$$\phi = \frac{W p_a}{0.6219 \cdot p_s}$$

Fundamental Parameters

7. Enthalpy of moist air mixtures

- For air-water vapor mixture, enthalpy is usually referenced to the mass of dry air, because the amount of water vapor may vary during the processes but the amount of dry air typically remains constant.

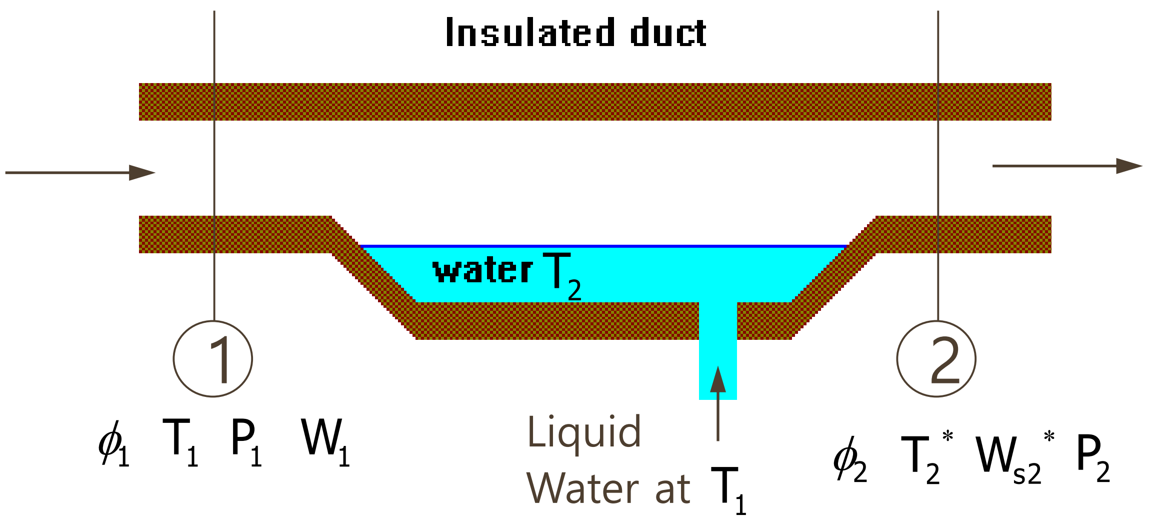
$$i = i_a + W \cdot i_v$$

For ideal gas, the enthalpy is a function of temp. only. If zero F and C is selected as the reference state, where Enthalpy of dry air is zero.

$$i_a = C_{pa} t \,, \qquad i_v = i_g + C_{pv} t$$

Adiabatic Saturation

- To determine the state (P, T and one more property) — (ϕ , W , or i) not easy to measure



Schematic of adiabatic saturation device

Adiabatic Saturation

- Assume adiabatic, steady state, no work

$$\begin{bmatrix} \text{Energy gives up by} \\ \text{entering air to water bath} \end{bmatrix} = \begin{bmatrix} \text{Energy lost by} \\ \text{bath due to evaporation rate} \end{bmatrix}$$

$t_2^* =$ adiabatic saturation temp. or thermodynamic wet bulb temp

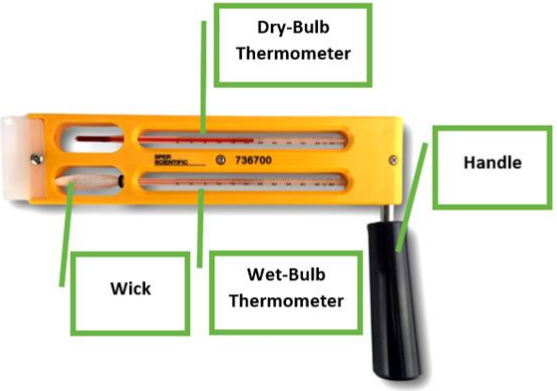
$$i_{a1} + W_1 \cdot i_{v1} + (W_{s2}^* - W_1) \cdot i_w^* = W_{s2}^* \cdot i_{v2}^* + i_{a2}^*$$

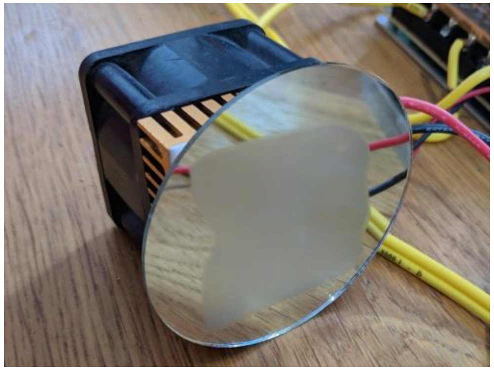
$$W_1 = \frac{C_{pa}(t_2^* - t_1) + W_{s2}^* \cdot i_{fg2}^*}{(i_{v1} - i_w^*)} \quad \left(\leftarrow W_2 = 0.6219 \frac{p_{s2}}{(p_2 - p_{s2})} \right)$$

Hygrometers

❑ Hygrometers

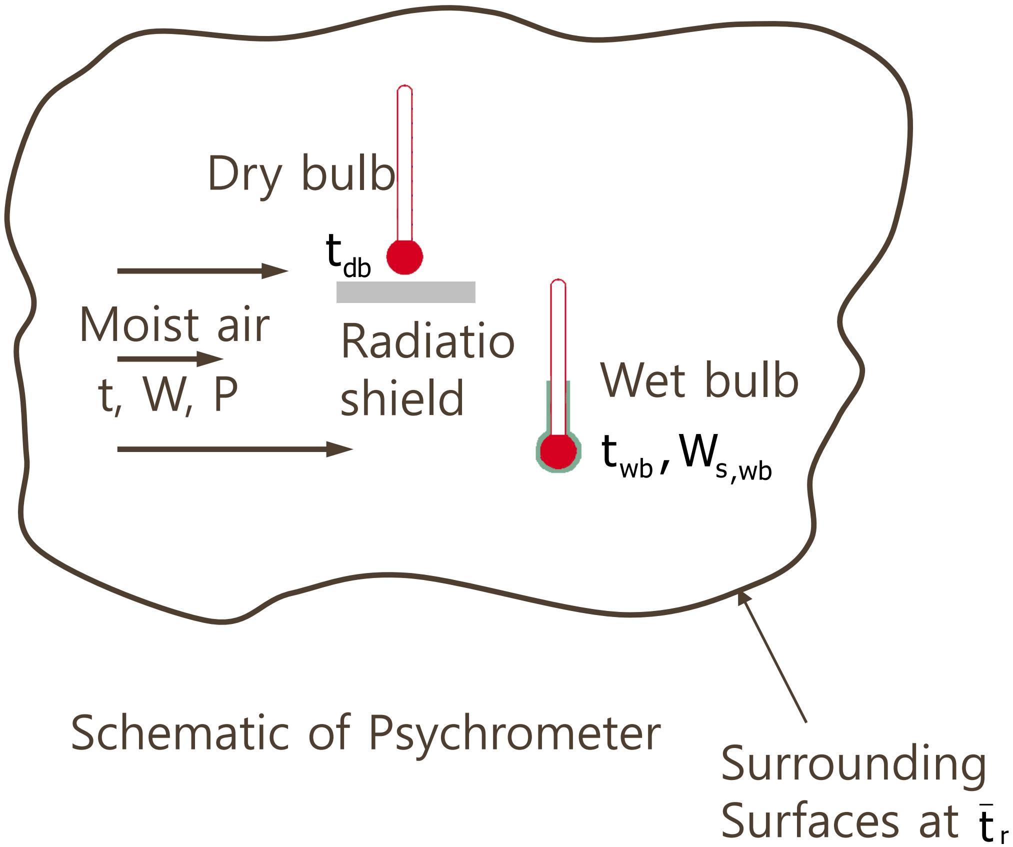
- Psychrometer
- Hair hygrometer
- Electronic hygrometer (Capacitive type)
- Electronic hygrometer (Resistive type)
- Gravimetric hygrometer
- Thermal hygrometer
- Chilled-mirror dewpoint hygrometer





Wet Bulb Temperature and Psychrometric chart

Theory of Psychrometer



Schematic of Psychrometer

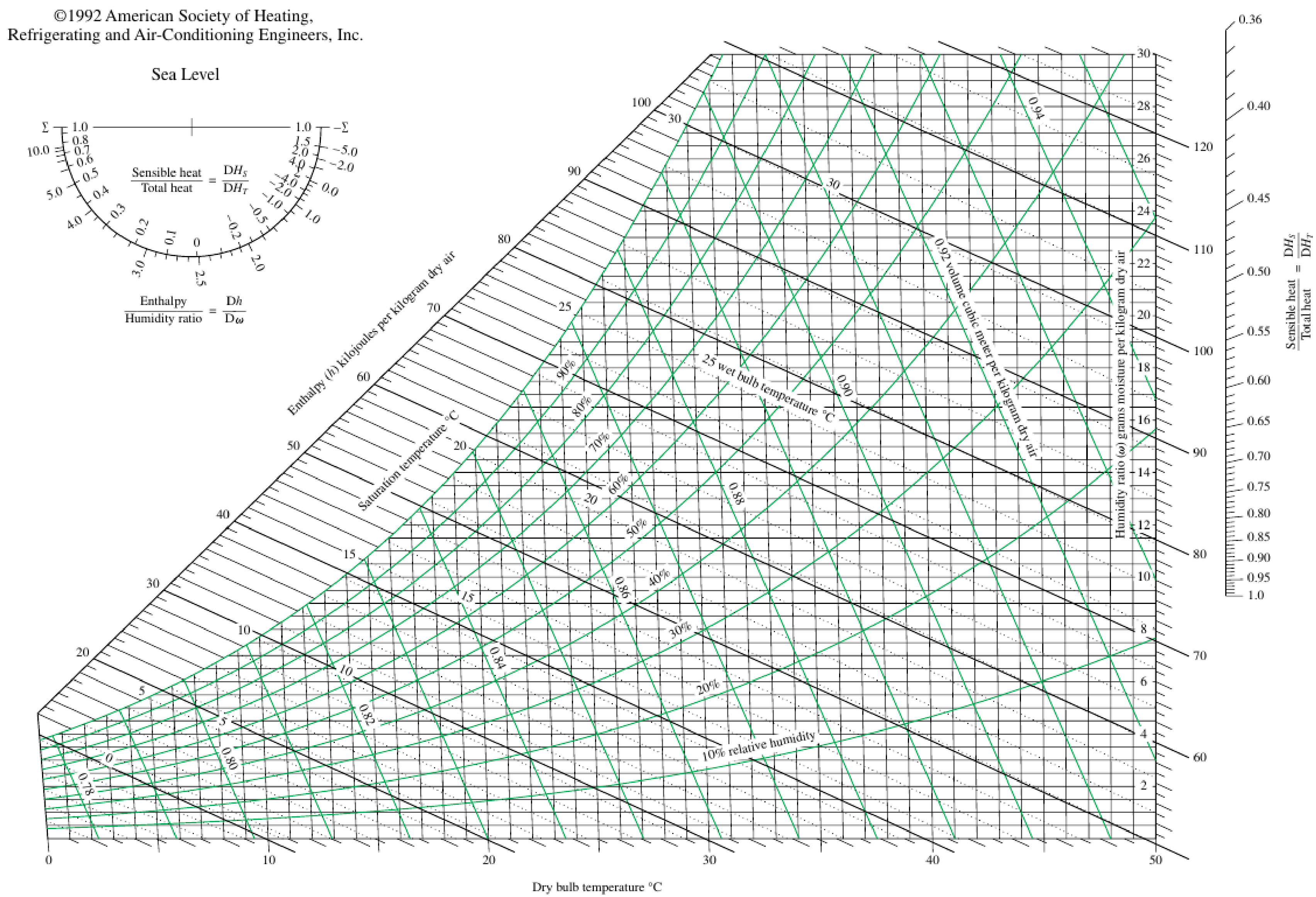
$$h_c(t_{db} - t) = h_r(\bar{t}_r - t_{db})$$

$$h_D(W_{s,wb} - W)h_{fg,wb} = h_c(t - t_{wb}) + h_r(\bar{t}_r - t_{wb})$$

$$\boxed{W = W_{s,wb} - K(t - t_{wb})}$$

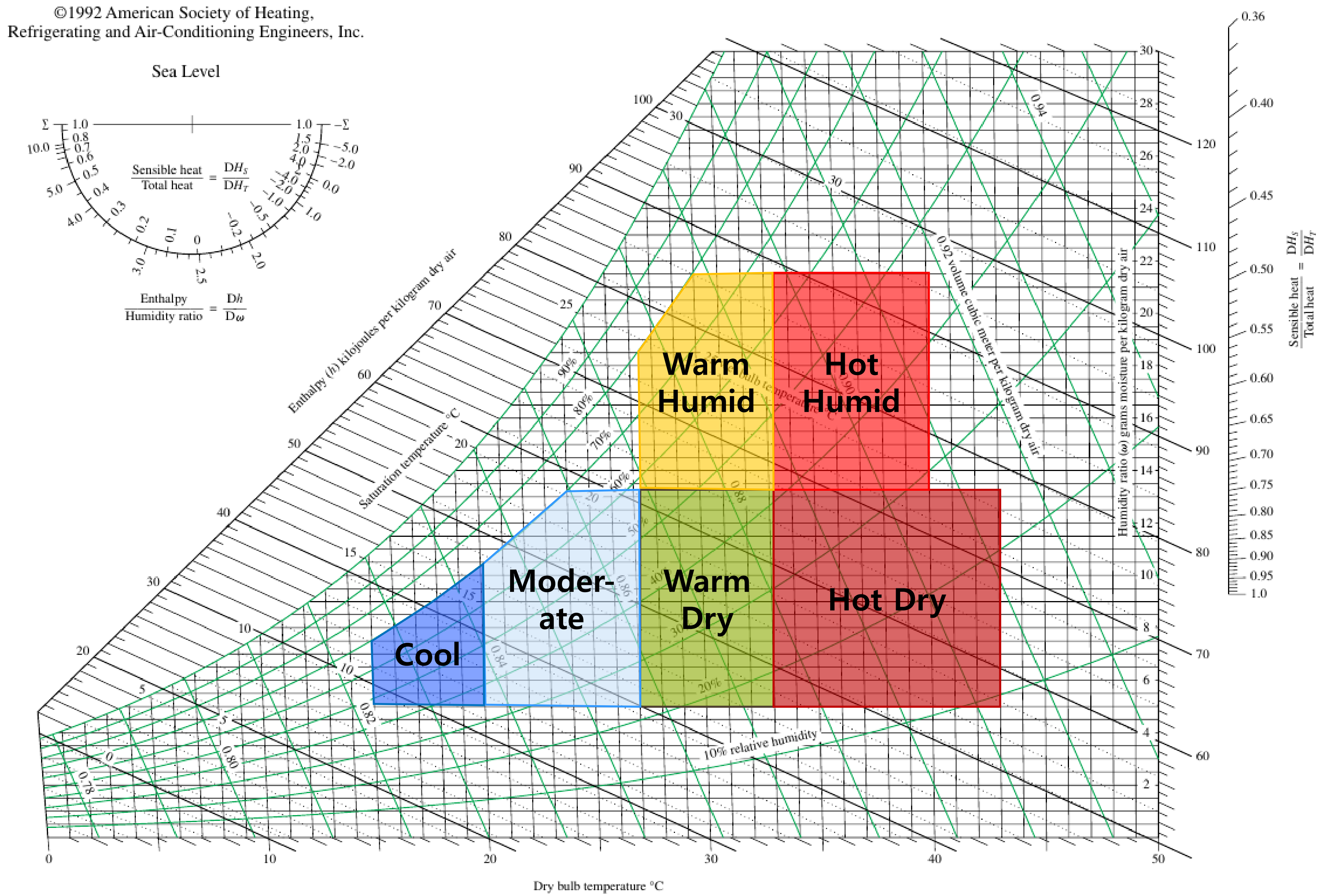
Moist Air Properties and Conditioning Processes

Wet Bulb Temperature and Psychrometric chart



Moist Air Properties and Conditioning Processes

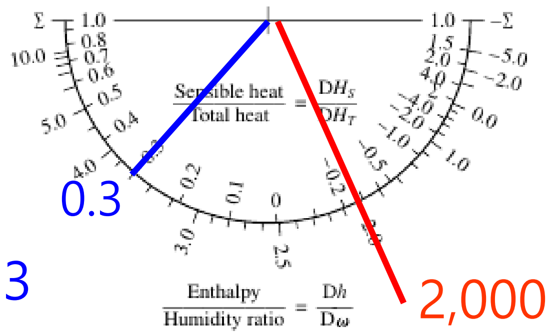
Psychrometric chart



Psychrometric chart

Protractor

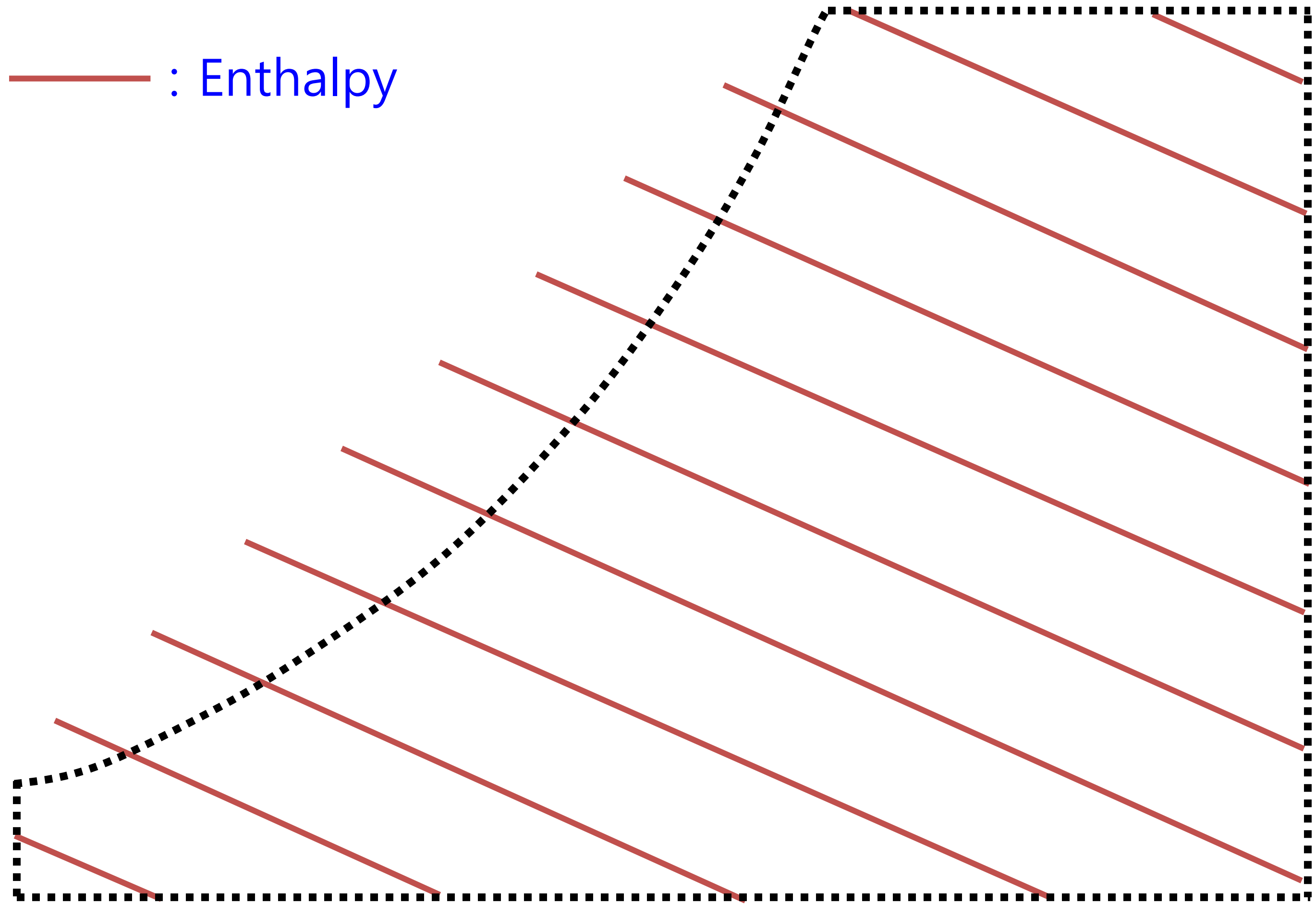
- SHF(sensible heat factor, 현열비) :
  - The ratio of change in sensible calories to enthalpy changes.



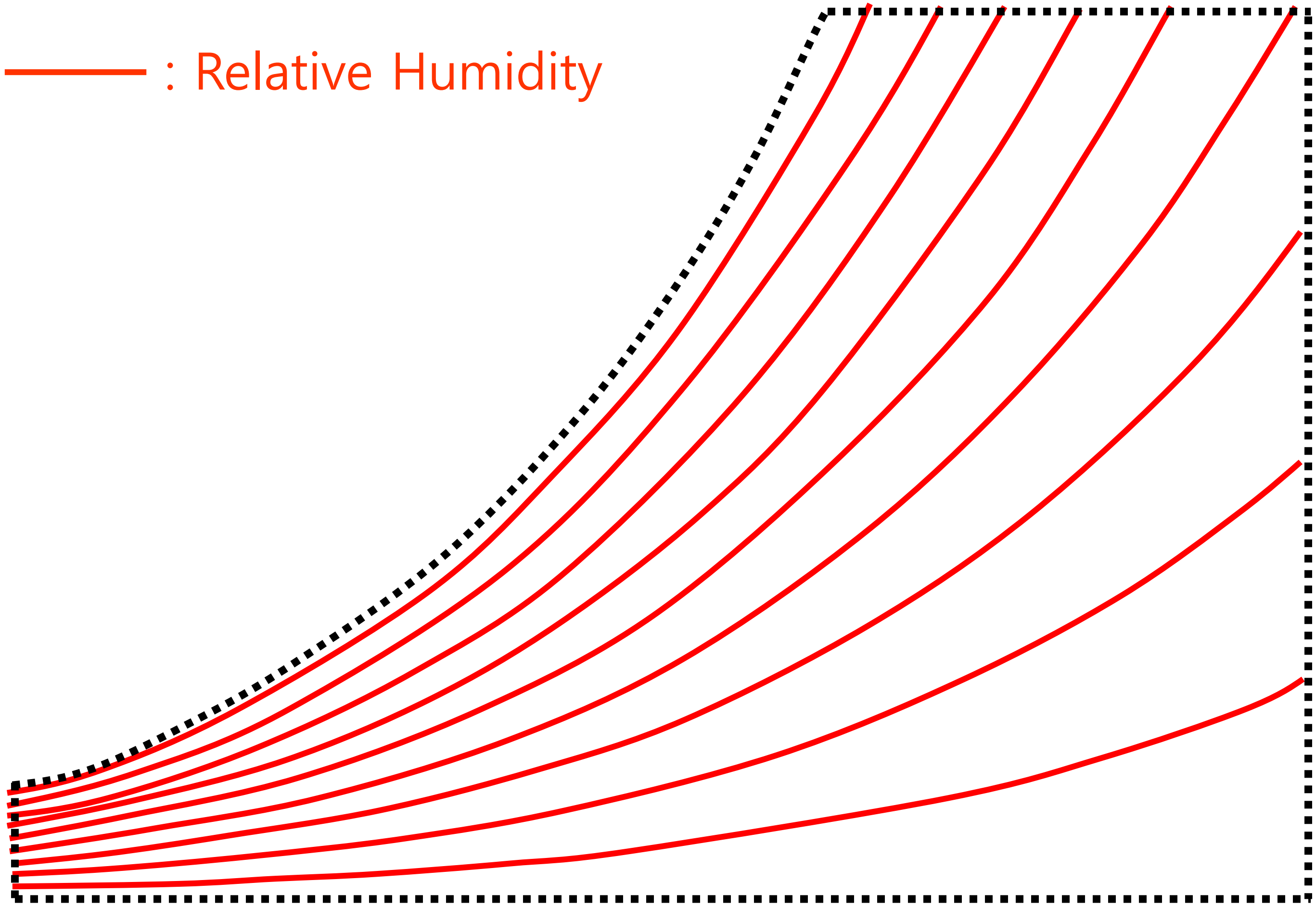
SHF = 0.3

$$\frac{\text{Enthalpy}}{\text{Humidity Ratio}} = \frac{\Delta h}{\Delta W} = 2{,}000$$

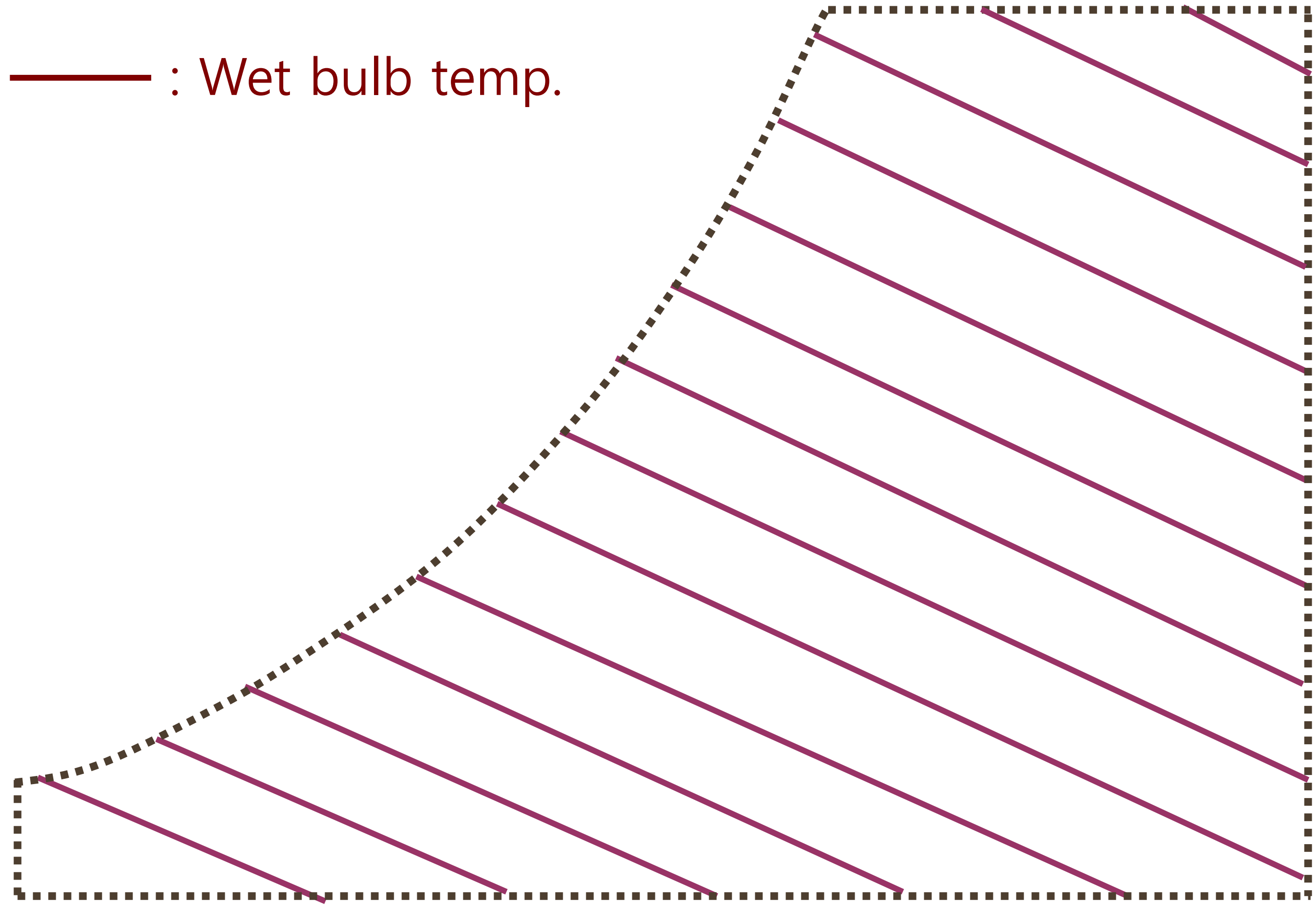
Psychrometric chart



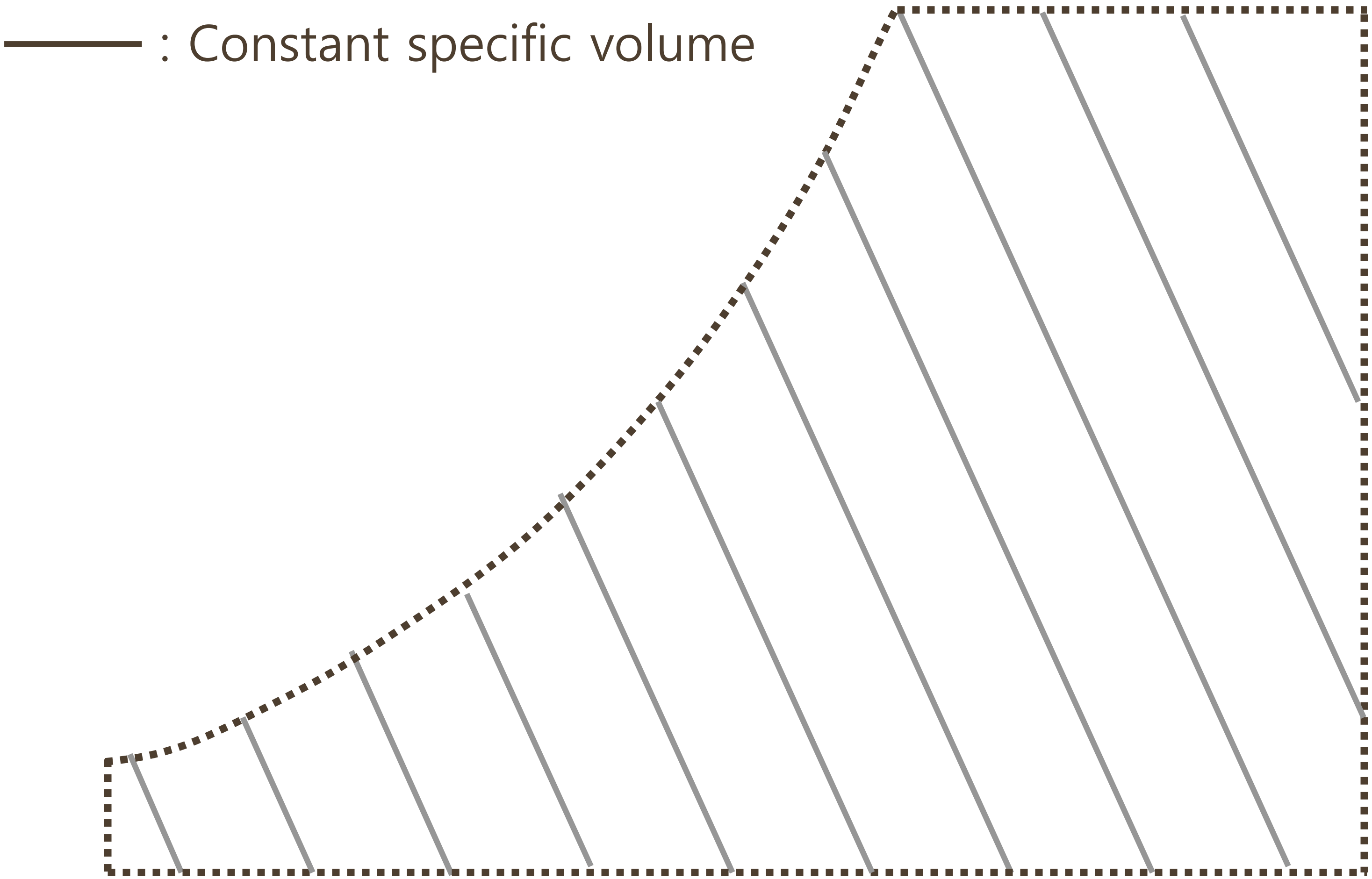
Psychrometric chart



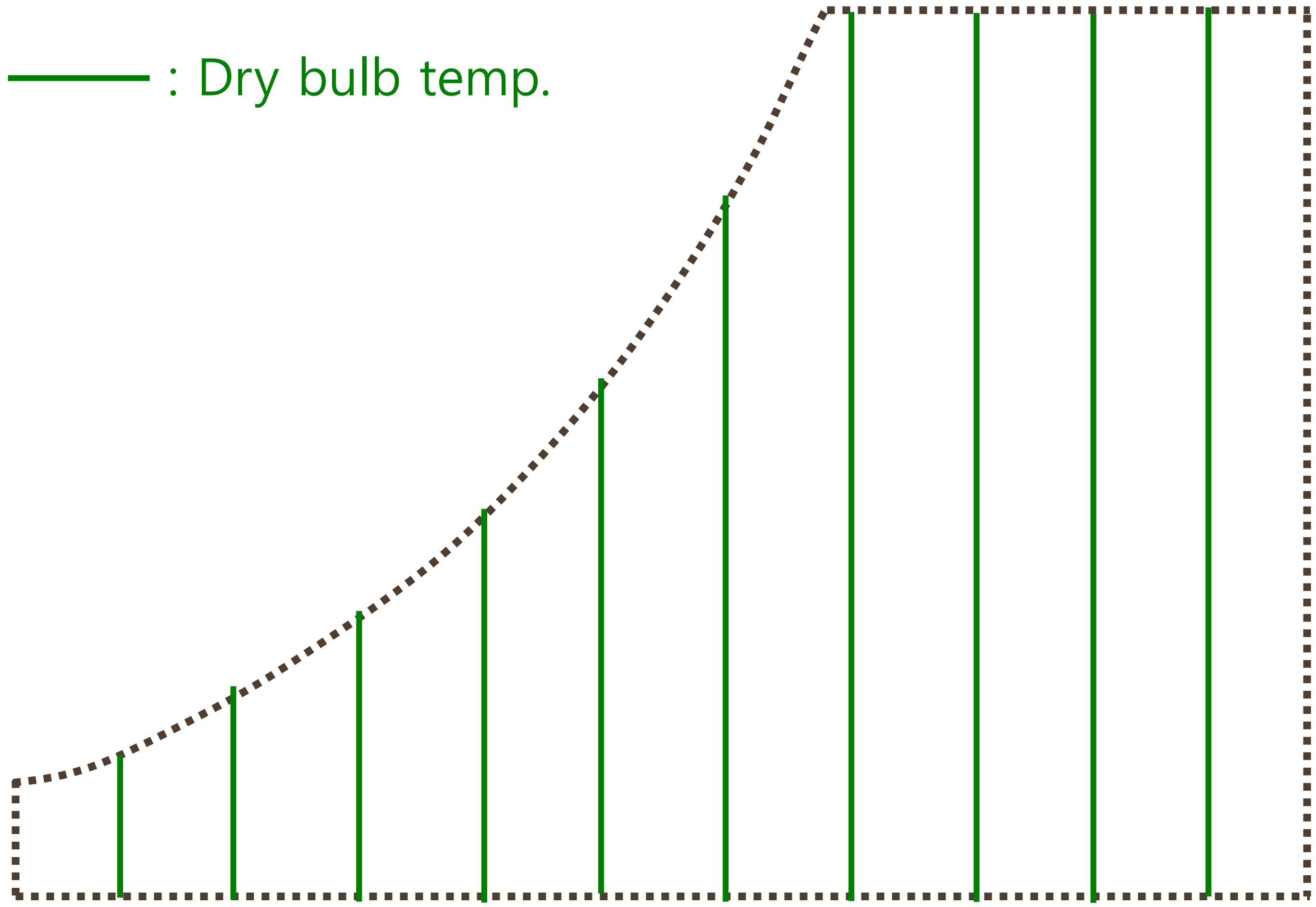
Psychrometric chart



Psychrometric chart



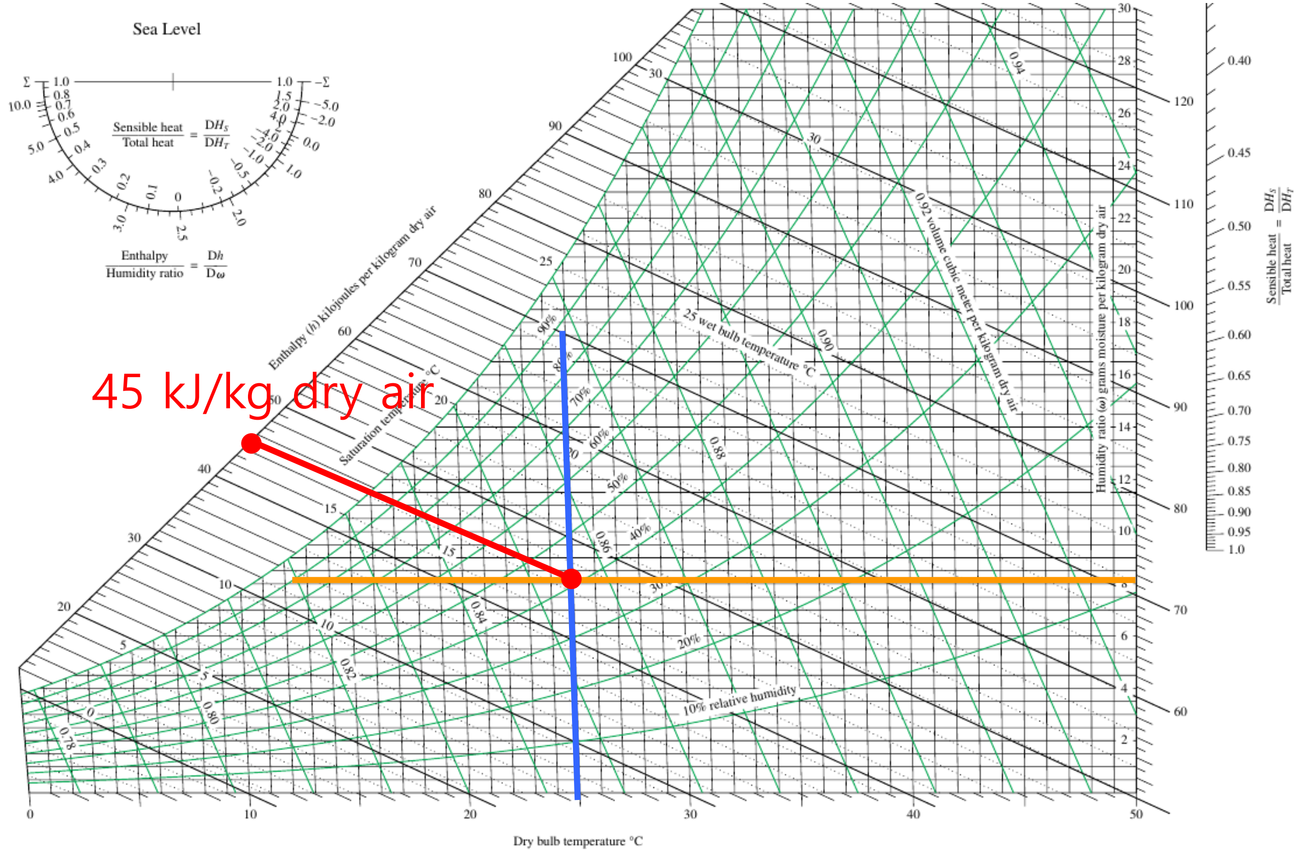
Psychrometric chart



How to Use PSYCHROMATRIC CHART?

Find enthalpy of point 1 for given condition

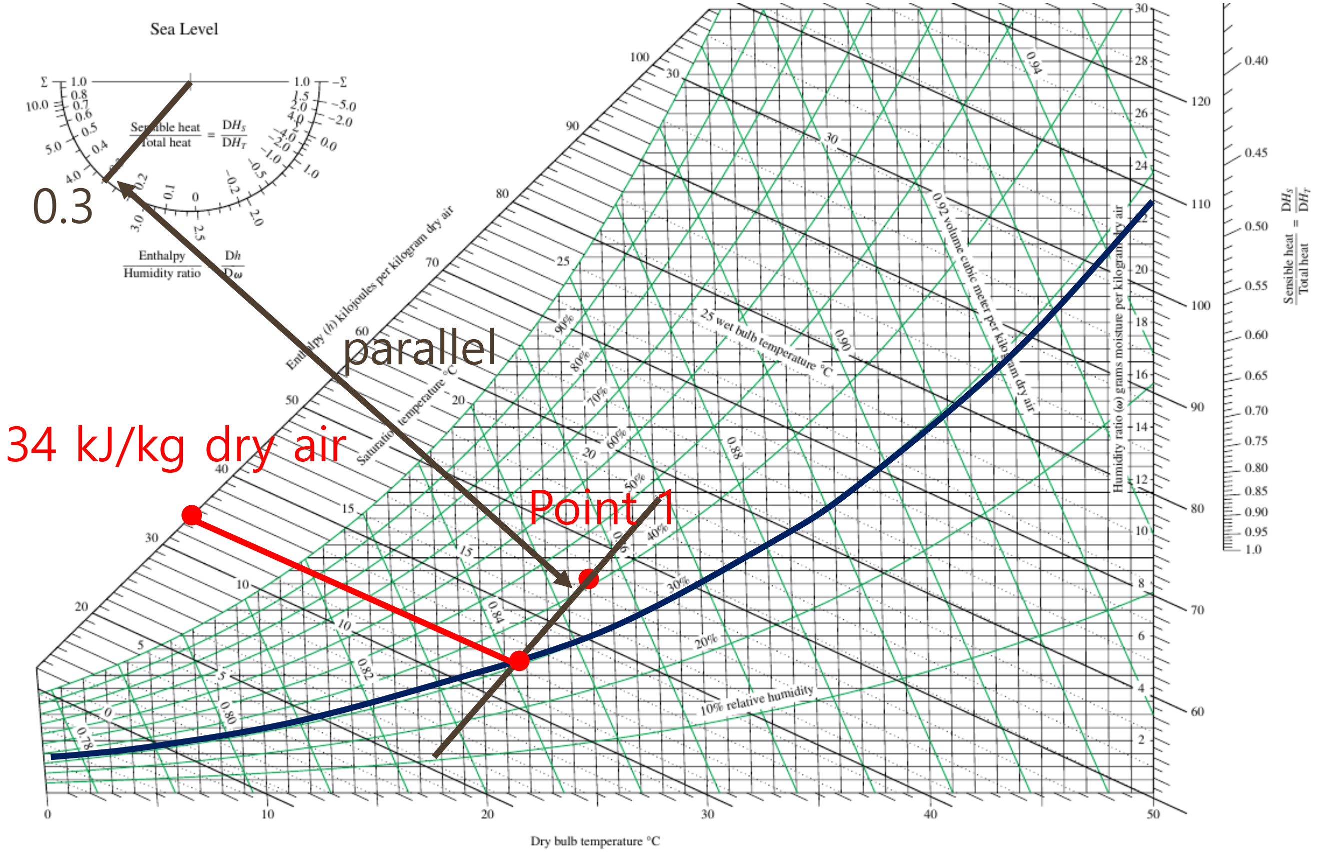
Dry bulb temp. = 25 ℃
W =8



How to Use PSYCHROMATRIC CHART?

Find enthalpy of point 2 for given condition

SHF = 0.3 (from point 1 to point 2)
point 2 is 30% relative humidity



Classic Moist Air Process

1) Heating or Cooling of Moist Air (1)

Energy balance

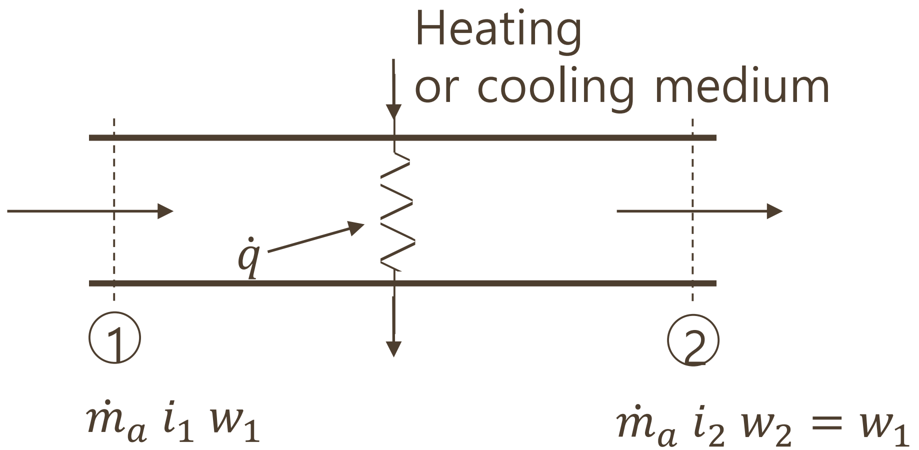
$$\dot{m}_a i_2 = \dot{m}_a i_1 + \dot{q}$$

Enthalpy of moist air

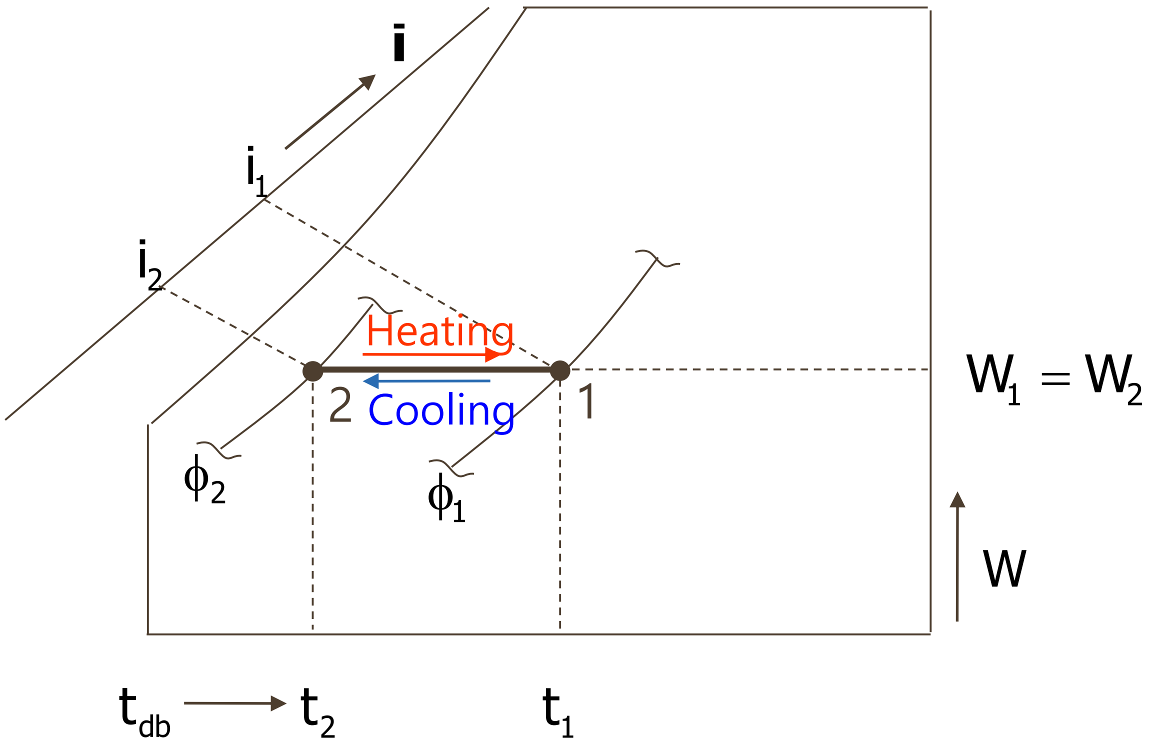
$$i_1 = i_{a1} + w_1 i_{v1}$$

$$i_2 = i_{a2} + w_2 i_{v2}$$

$$\dot{q}_s = \dot{m}_a c_p (T_1 - T_2)$$



Classic Moist Air Process



Psychrometric diagram for heating and cooling system

Classic Moist Air Process

2) Cooling and Dehumidifying of Moist Air

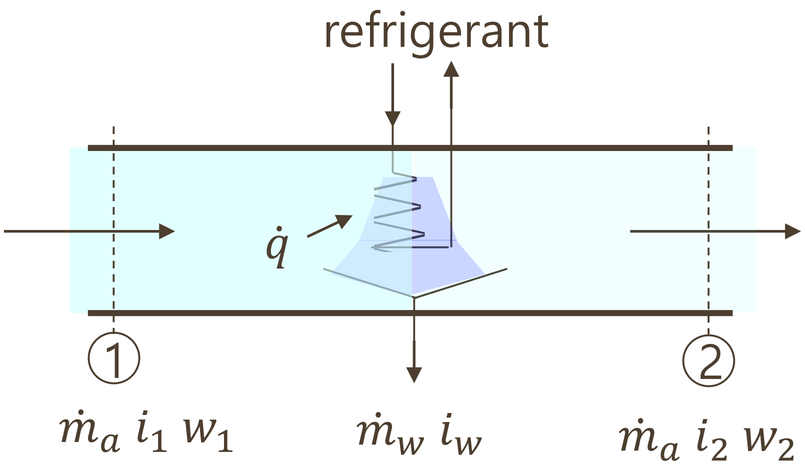
Energy balance

$$\dot{m}_a i_1 = \dot{q} + \dot{m}_a i_2 + \dot{m}_w i_w$$

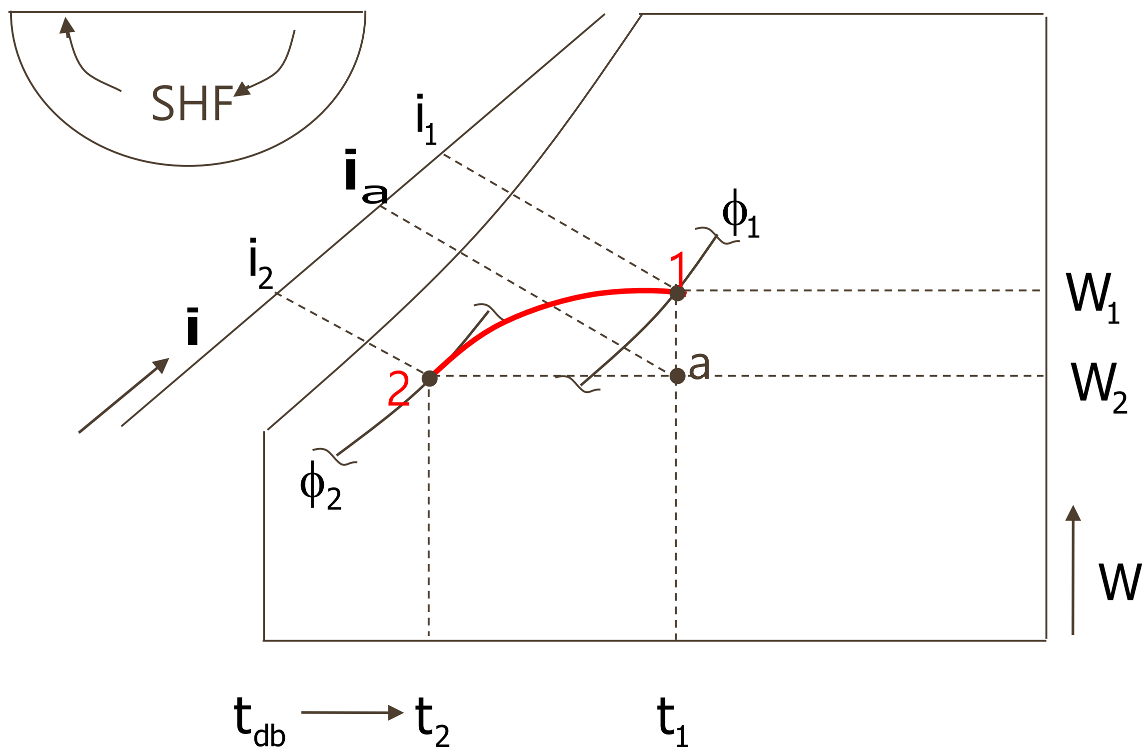
Mass balance

$$\dot{m}_a w_1 = \dot{m}_w + \dot{m}_a w_2$$

$$\dot{q} = \dot{m}_a (i_1 - i_2) - \dot{m}_a (w_1 - w_2) i_w$$



Classic Moist Air Process



Psychrometric diagram for cooling and dehumidifying system

Classic Moist Air Process

3) Heating and Humidifying Moist Air

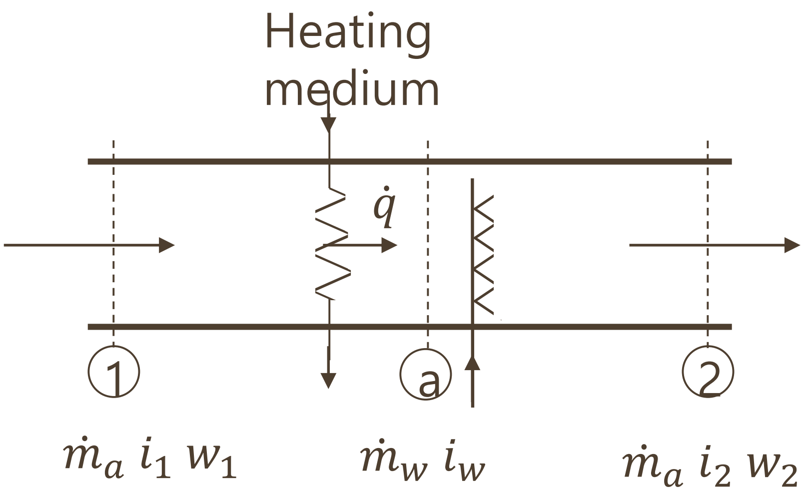
Energy balance

$$\dot{m}_a i_1 + \dot{q} + \dot{m}_w i_w = \dot{m}_a i_2$$

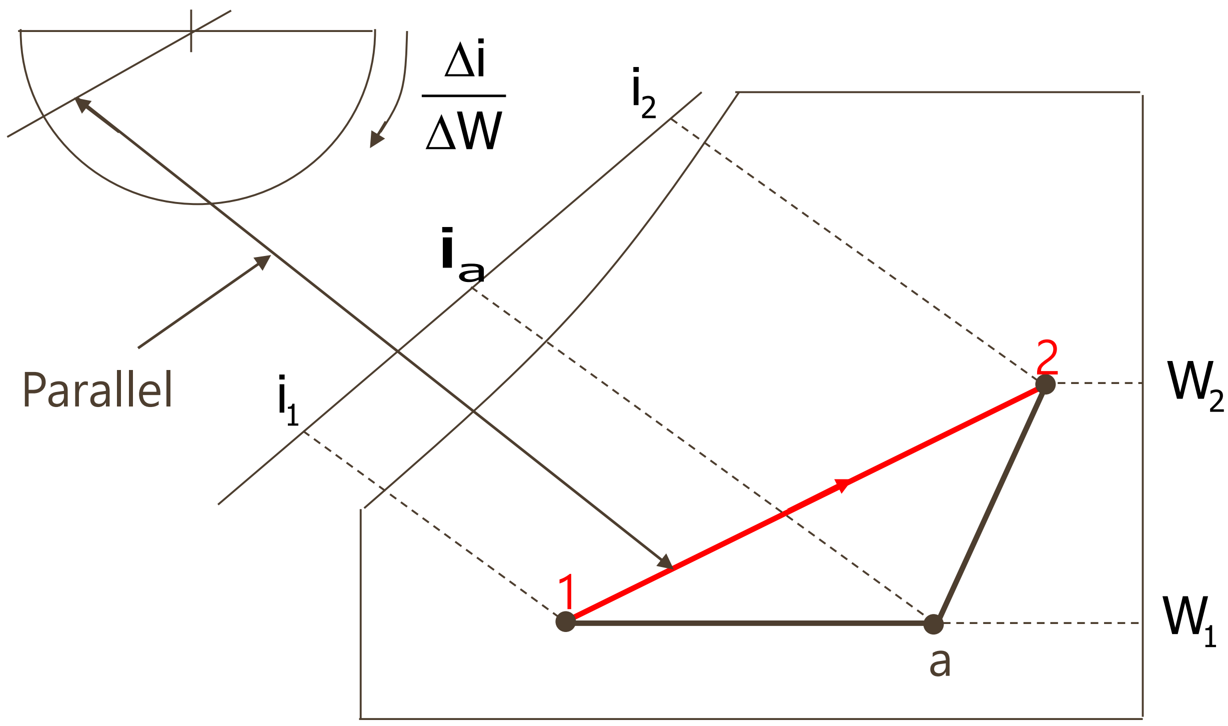
Mass balance

$$\dot{m}_a w_1 = \dot{m}_w + \dot{m}_a w_2$$

$$\frac{i_2 - i_1}{w_2 - w_1} = \frac{\dot{q}}{\dot{m}_a (w_2 - w_1)} + i_w$$



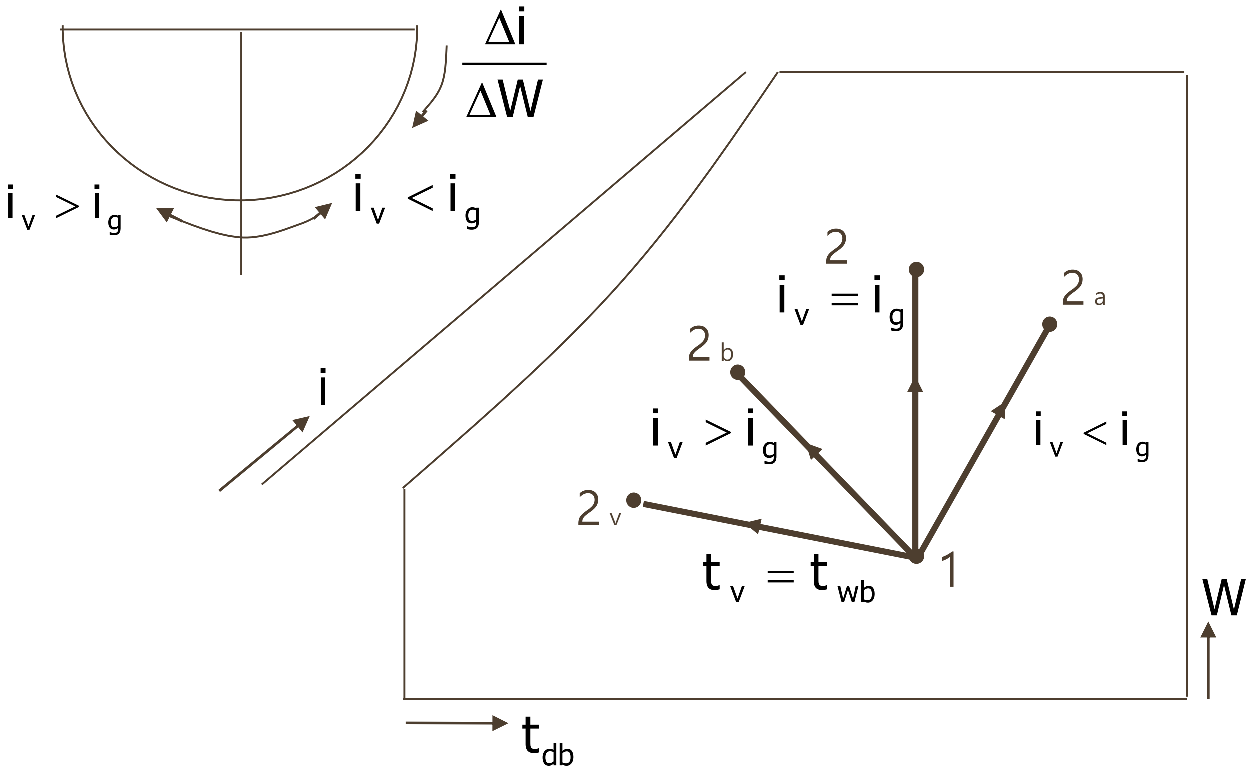
Classic Moist Air Process



Psychrometric diagram for heating and humidifying system

Classic Moist Air Process

4) Adiabatic Humidification of Moist Air (1)



Classic Moist Air Process

4) Adiabatic Humidification of Moist Air (1)

- Moisture added to moist air without addition of heat

$$\frac{i_2 - i_1}{W_2 - W_1} = i_w = \frac{\Delta i}{\Delta W}$$

- Direction of process

ⓐ the injected water is saturated vapor at dry bulb temp.
$t_{db} = \text{const.}$

ⓑ $i_w > i_g$ (enthalpy of saturated vapor at db temp.)

air heated and humidified

ⓒ $i_w < i_g$: air is cooled and humidified

ⓓ liquid water $t_w = t_{wb}$: constant wet bulb temperature

Classic Moist Air Process

5) Adiabatic Mixing of Two Streams of Moist Air

Energy Balance

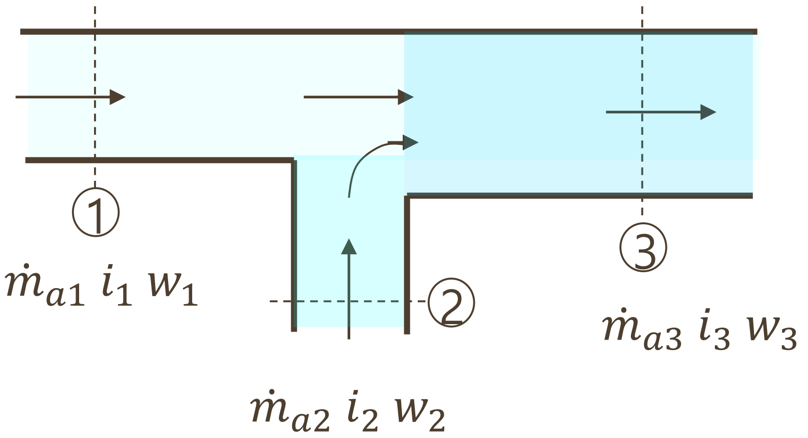
$$\dot{m}_{a1}i_1 + \dot{m}_{a2}i_2 = \dot{m}_{a3}i_3$$

Mass balance of dry air

$$\dot{m}_{a1} + \dot{m}_{a2} = \dot{m}_{a3}$$

Mass balance of water air

$$\dot{m}_{a1}w_1 + \dot{m}_{a2}w_2 = \dot{m}_{a3}w_3$$



Classic Moist Air Process

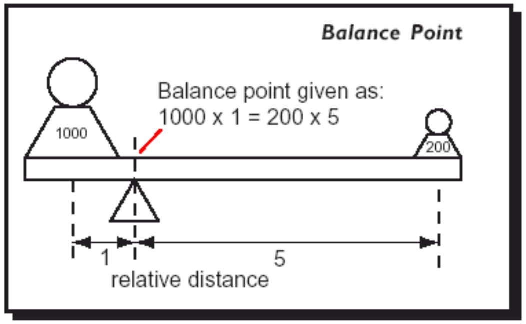
(1) Mathematical approach

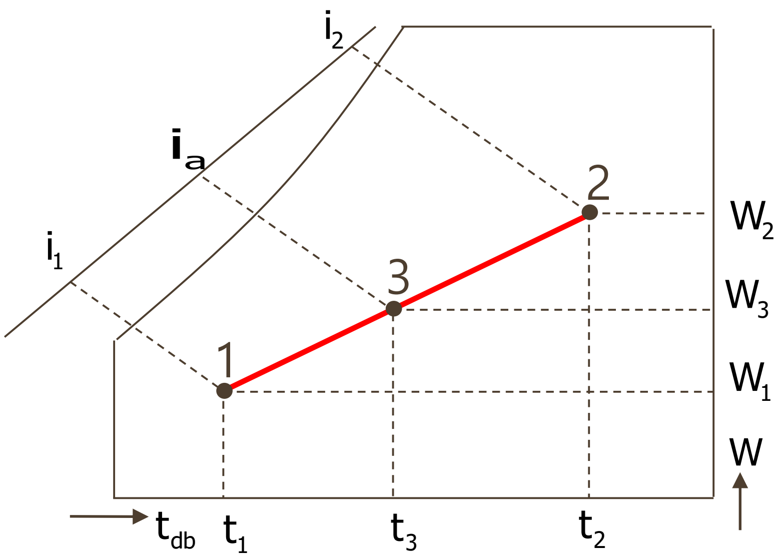
$$\frac{i_2 - i_3}{i_3 - i_1} = \frac{w_2 - w_3}{w_3 - w_1} = \frac{\dot{m}_{a1}}{\dot{m}_{a2}}$$

(2) Graphical approach

$$\frac{\dot{m}_{a1}}{\dot{m}_{a2}} = \frac{\overline{32}}{\overline{13}} \qquad \frac{\dot{m}_{a1}}{\dot{m}_{a3}} = \frac{\overline{32}}{\overline{12}} \qquad \frac{\dot{m}_{a2}}{\dot{m}_{a3}} = \frac{\overline{13}}{\overline{12}}$$

Tip $\frac{Q_1}{Q_2} \neq \frac{m_1}{m_2}$



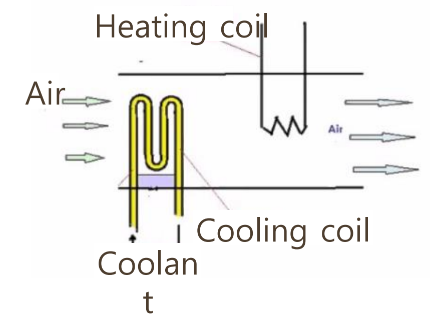


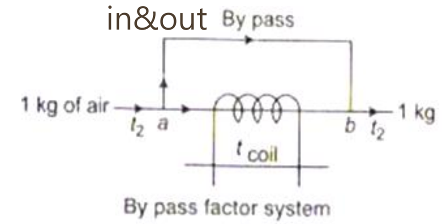
Classic Moist Air Process

6) Space Air Conditioning – Design Condition

- **Sensible Heat Factor (SHF)**

$$SHF = \frac{\dot{q}_s}{\dot{q}_s + \dot{q}_l} = \frac{\dot{q}_s}{\dot{q}}$$





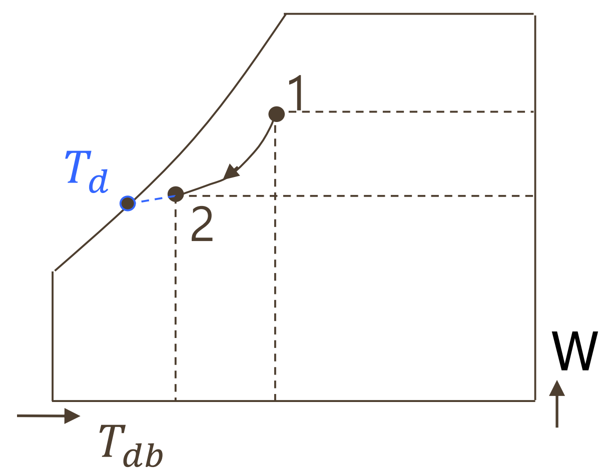
- **Bypass Factor (BPF, b)**

$$b = \frac{\text{Amount of air bypassing the coil}}{\text{Total amount of air passed}} = \frac{T_2 - T_d}{T_1 - T_d}$$

$$1 - b = \frac{T_1 - T_2}{T_1 - T_d}$$

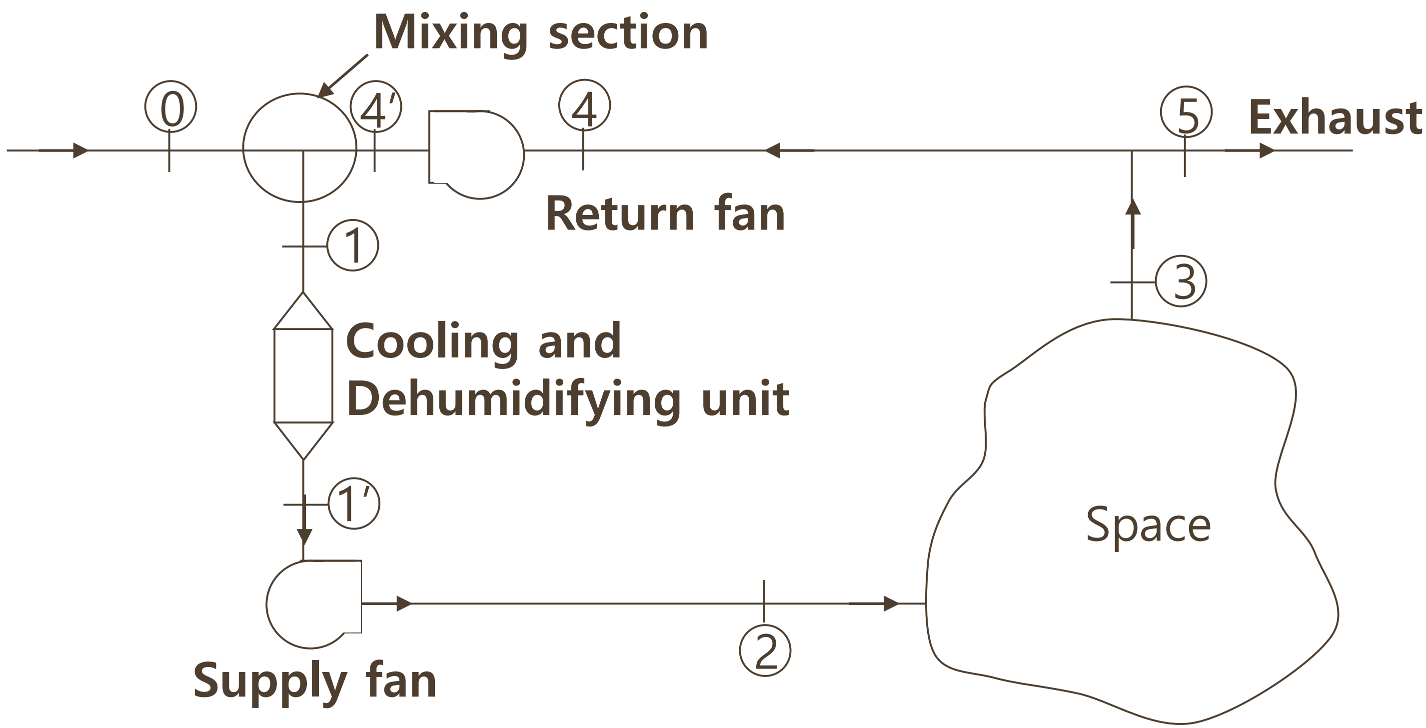
$$\dot{q}_{cs} = \dot{m}_{a1} c_p (T_1 - T_2)$$

$$\dot{q}_{cs} = \dot{m}_{a1} c_p (T_1 - T_d)(1 - b)$$



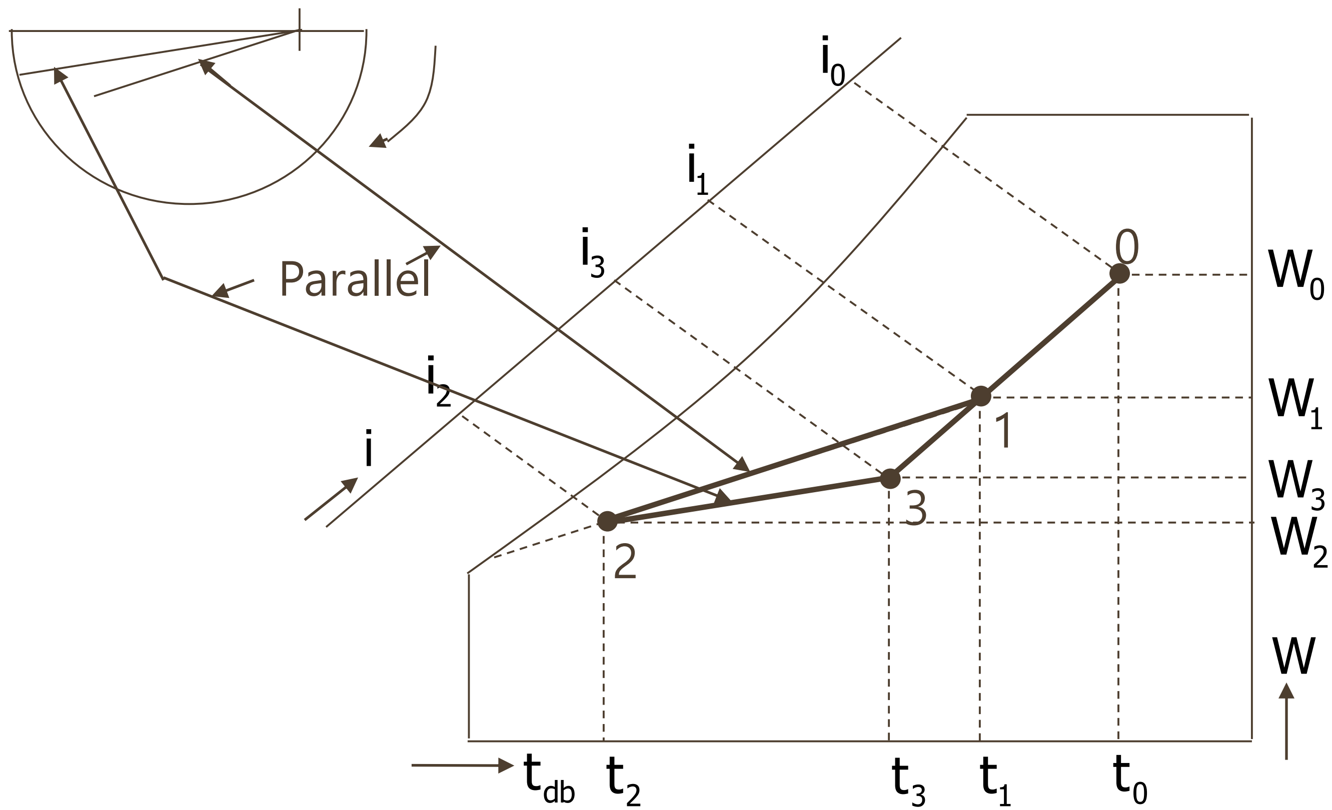
Classic Moist Air Process

6) Space Air Conditioning – Design Condition (2)



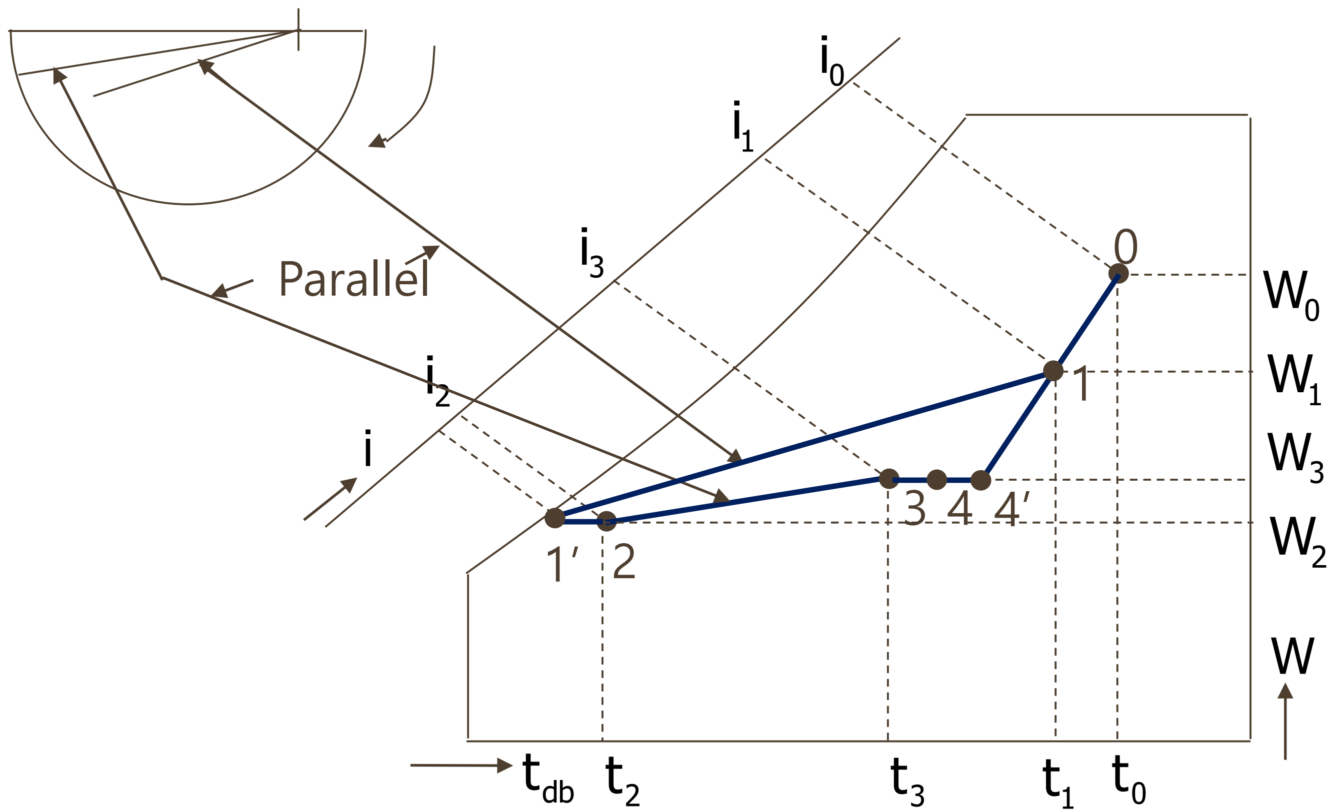
Single – line sketch of cooling and dehumidifying system

Classic Moist Air Process



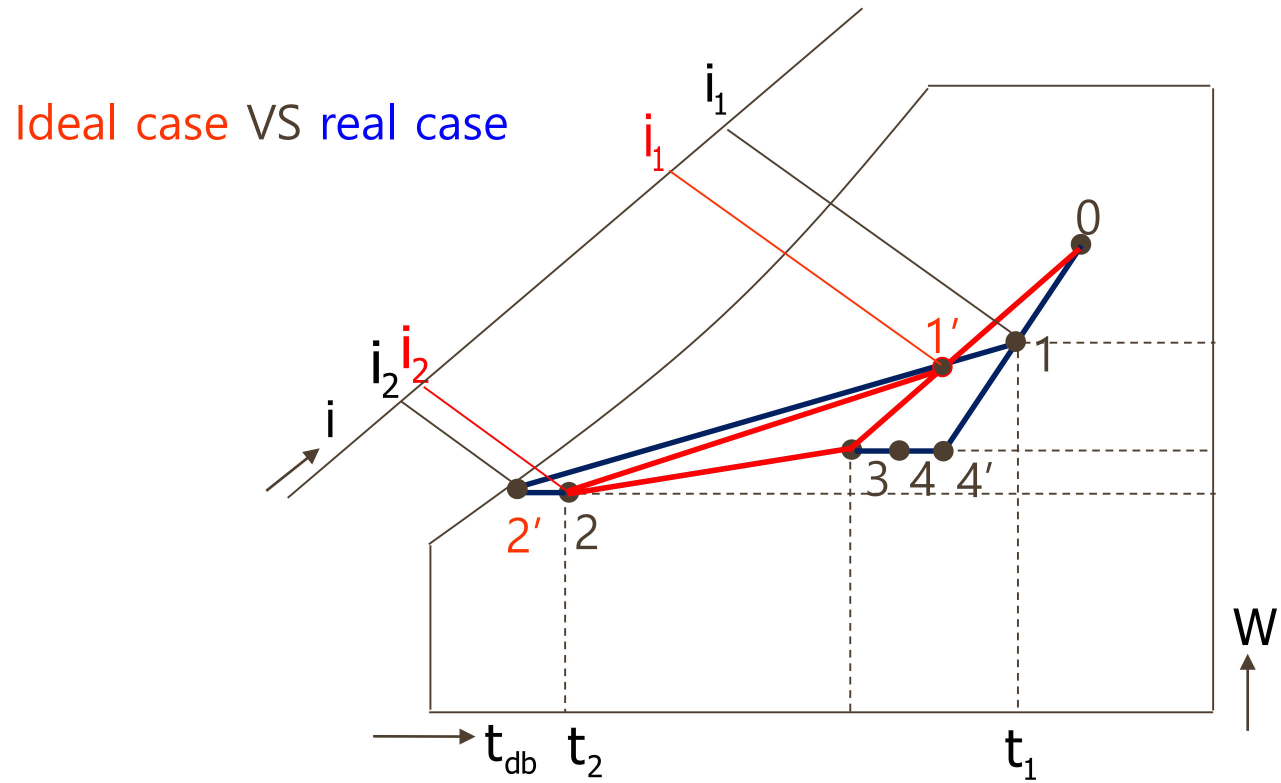
Psychrometric process

Classic Moist Air Process



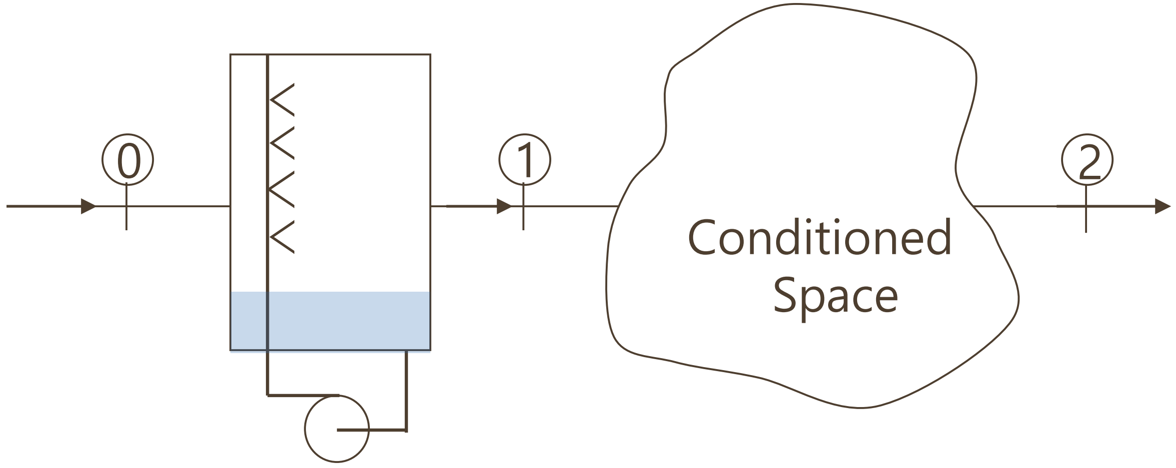
Psychrometric process, showing the effect of fans and heat gain

Classic Moist Air Process



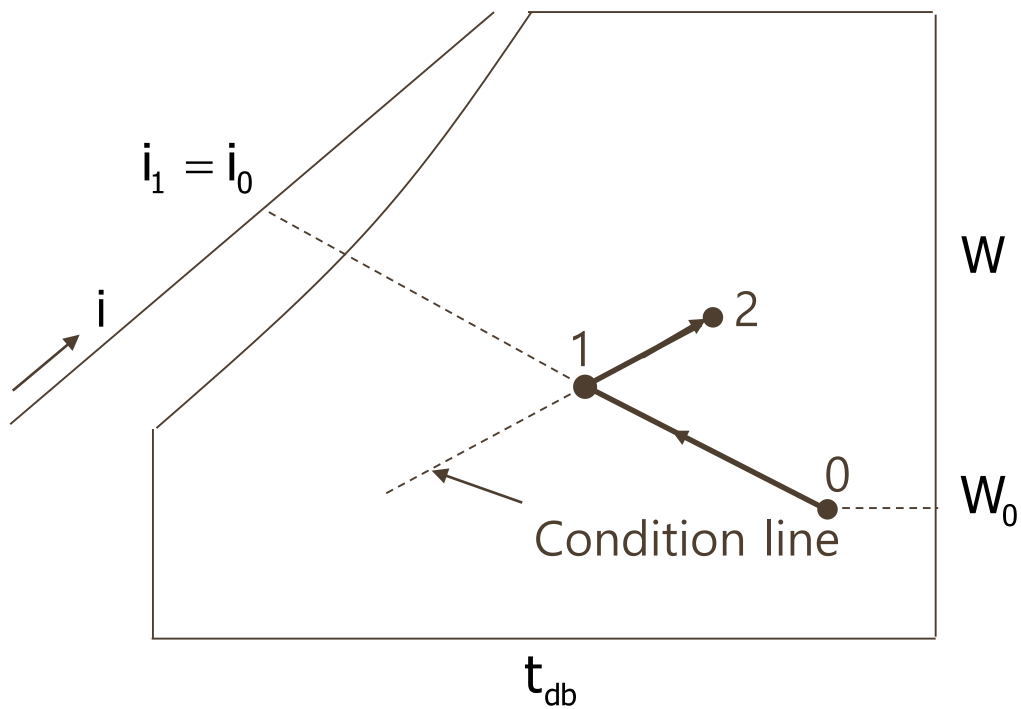
Classic Moist Air Process

7) Evaporative Cooling System (1)



A simple evaporative cooling system

Classic Moist Air Process



Psychrometric process for the evaporative cooling system

Classic Moist Air Process

❑ Characteristics of EVAPORATIVE COOLING

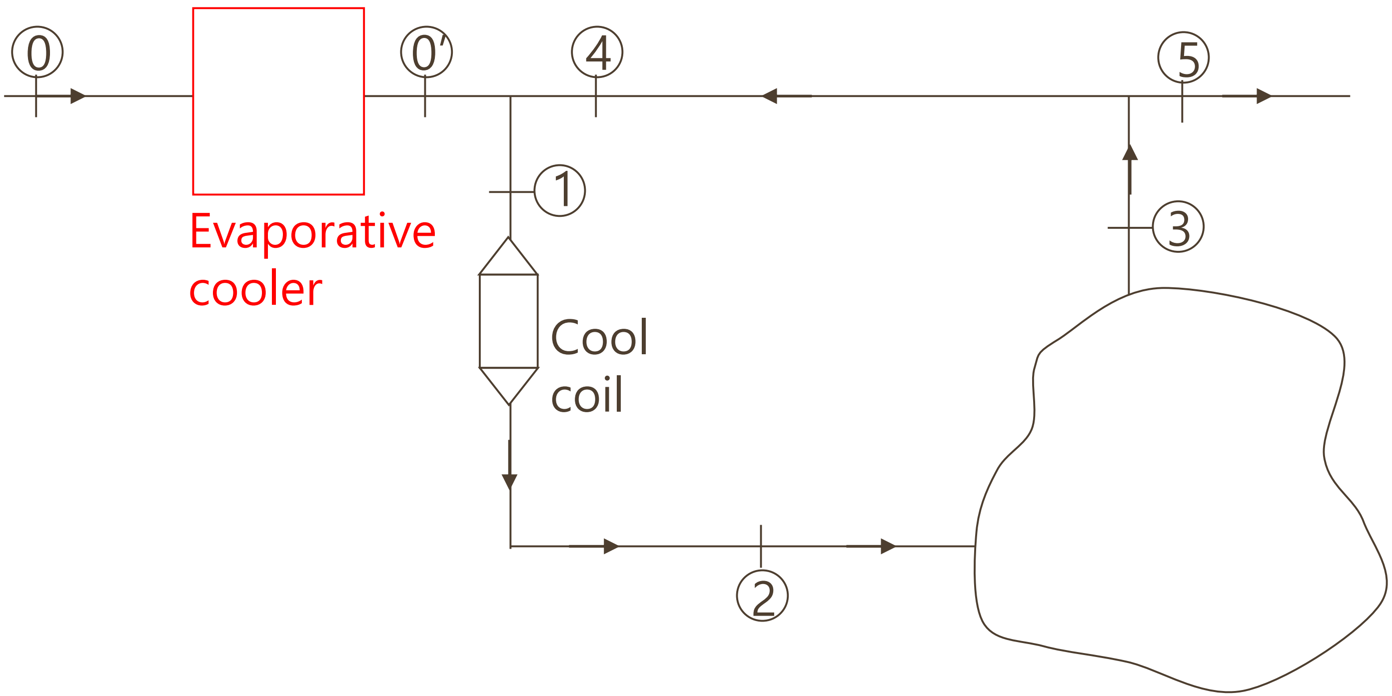
1. **Advantage under hot and dry air condition**
   The dry and hot outdoor air flows through an adiabatic spay chamber and is cooled and humidified, but where the outdoor relative humidity is high, this system is not satisfactory.
   (∵If relative humidity is high, process can't intersect the condition line)

2. **Reducing power for sensible cooling**

3. **The air supplied to the space will be 100% outdoor air**

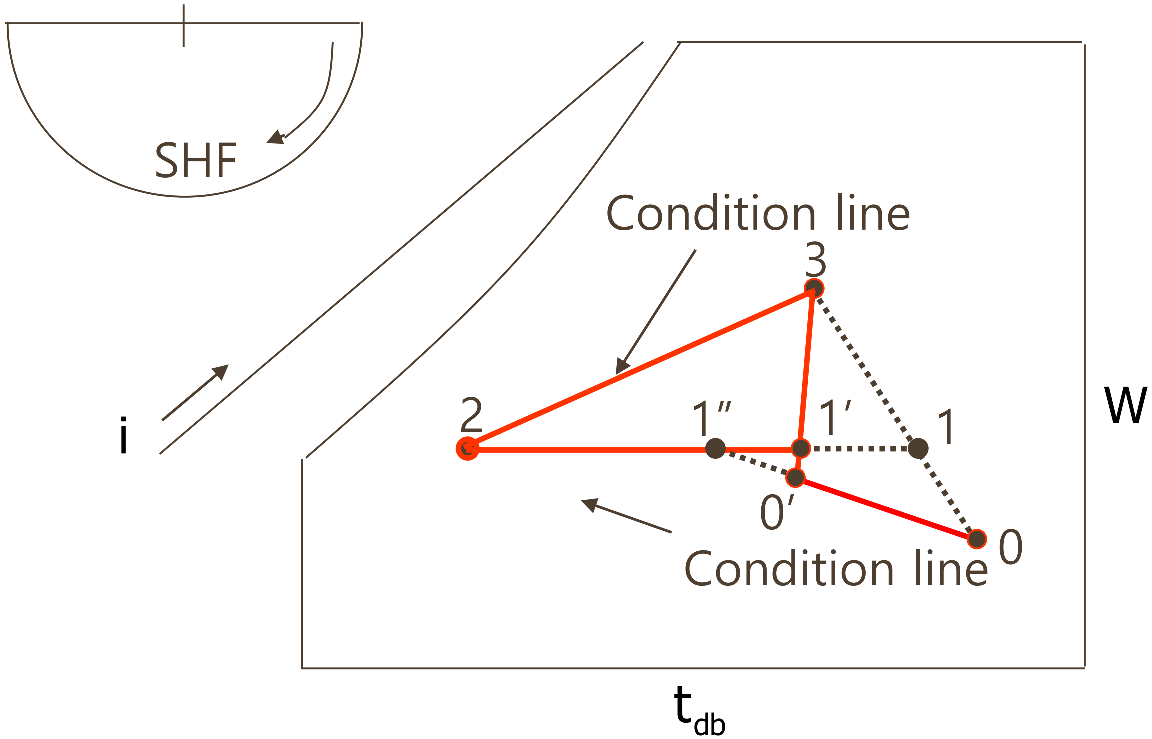
Classic Moist Air Process

7) Evaporative Cooling System (2)



Heating system with preheat of outdoor air

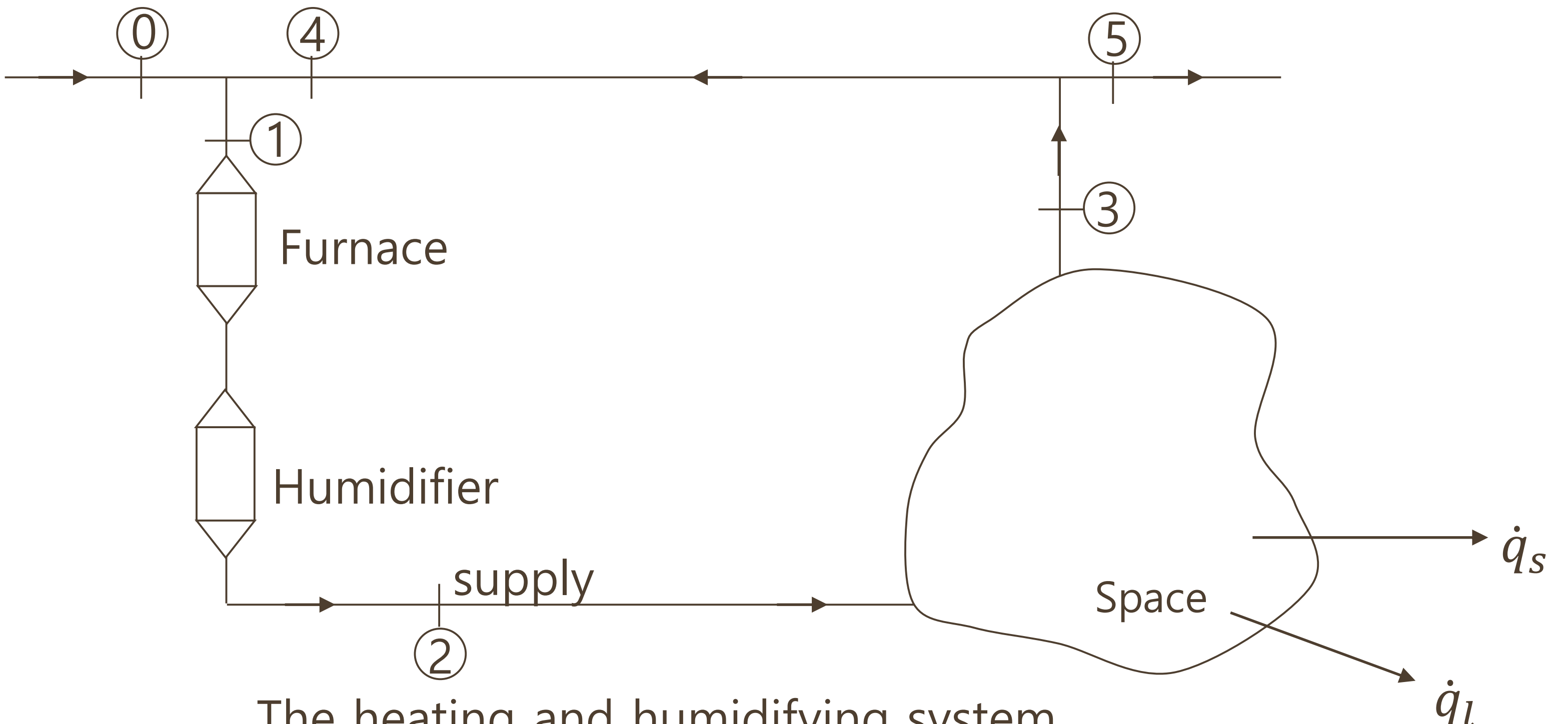
Classic Moist Air Process



Psychrometric diagram for combination evaporative and regular cooling system

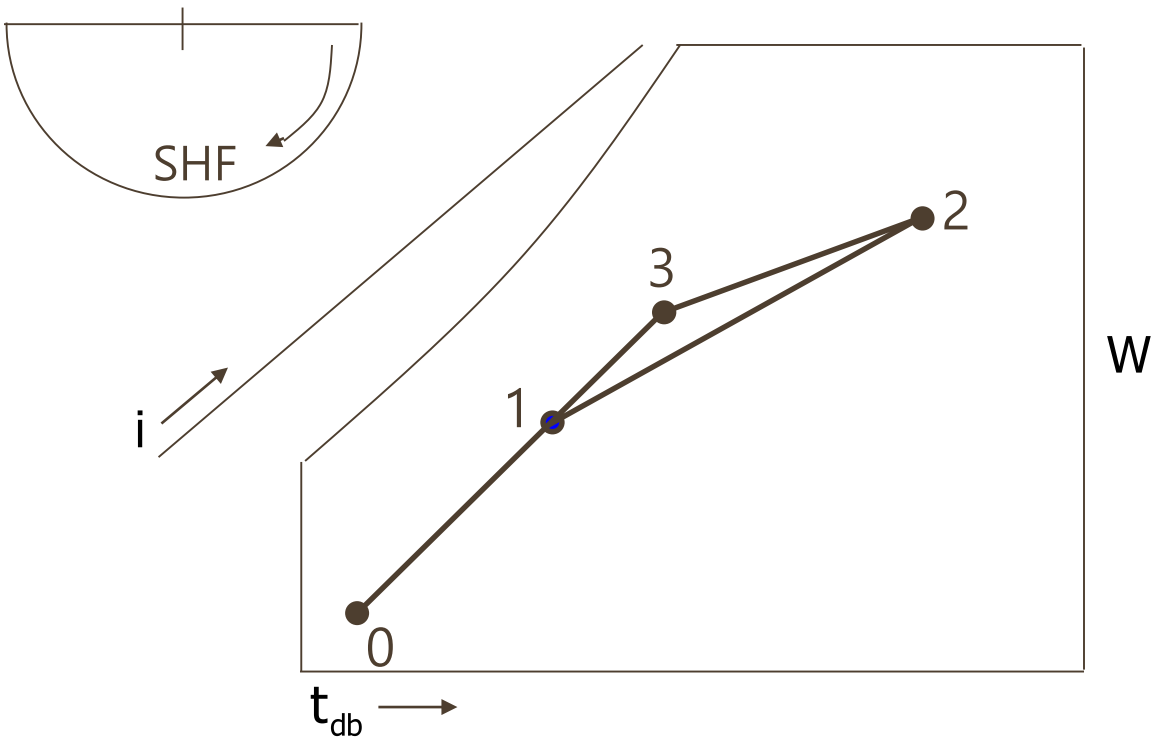
Classic Moist Air Process

8) Other space air conditioning (1)



The heating and humidifying system

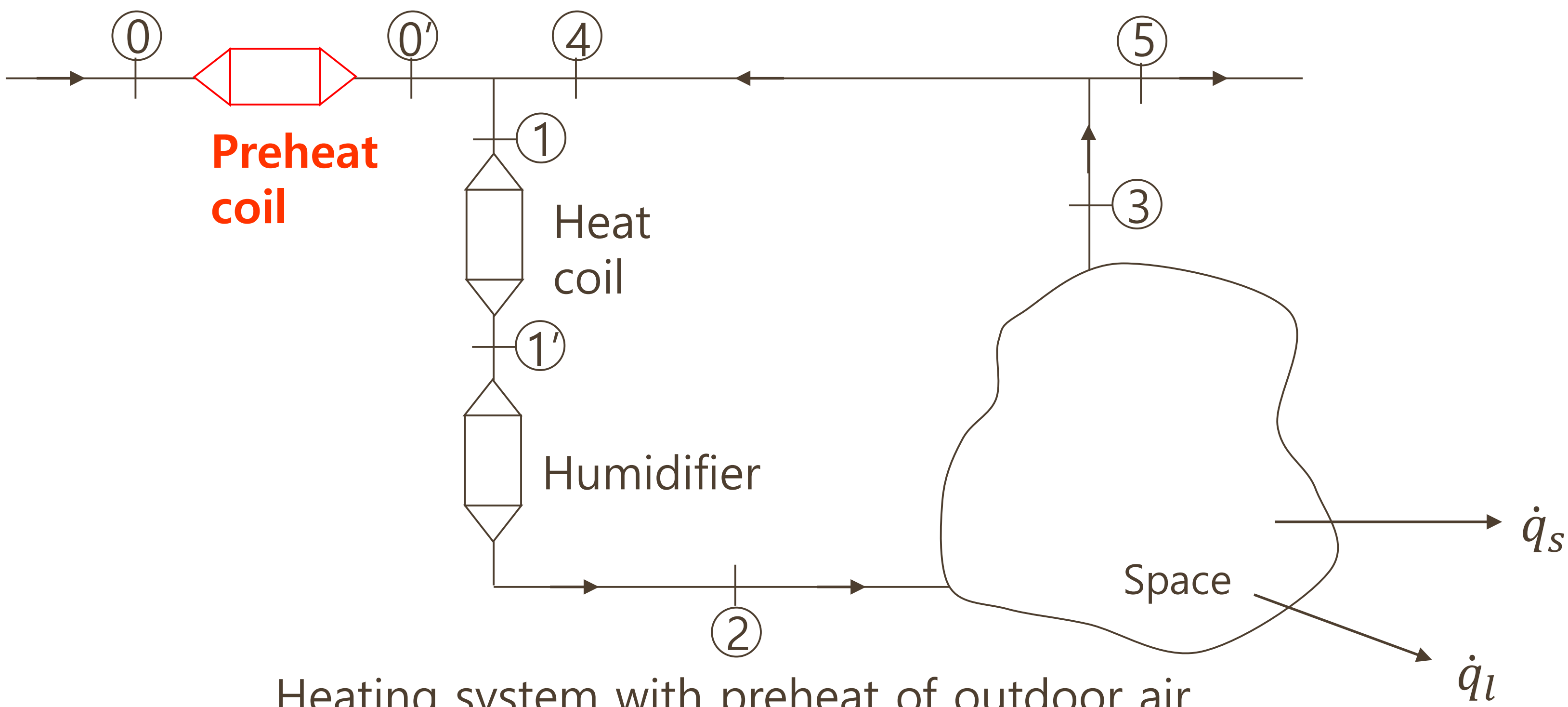
Classic Moist Air Process



Psychrometric diagram for heating and humidifying system

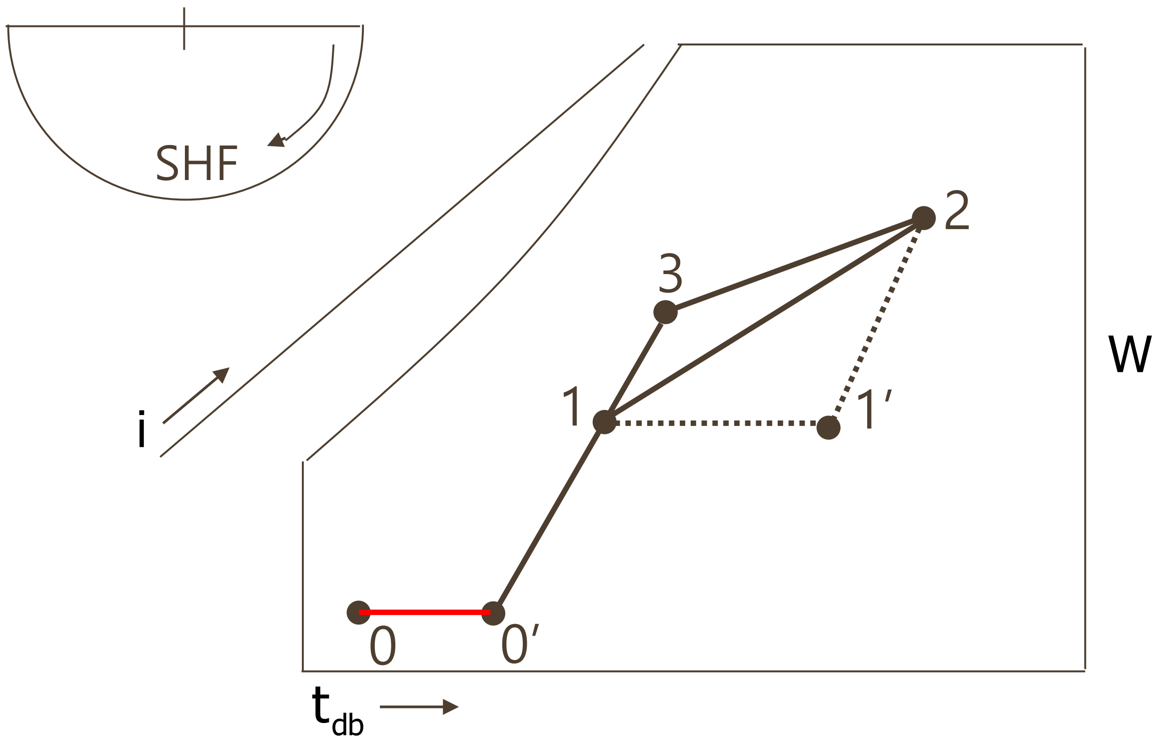
Classic Moist Air Process

8) Other space air conditioning (2)



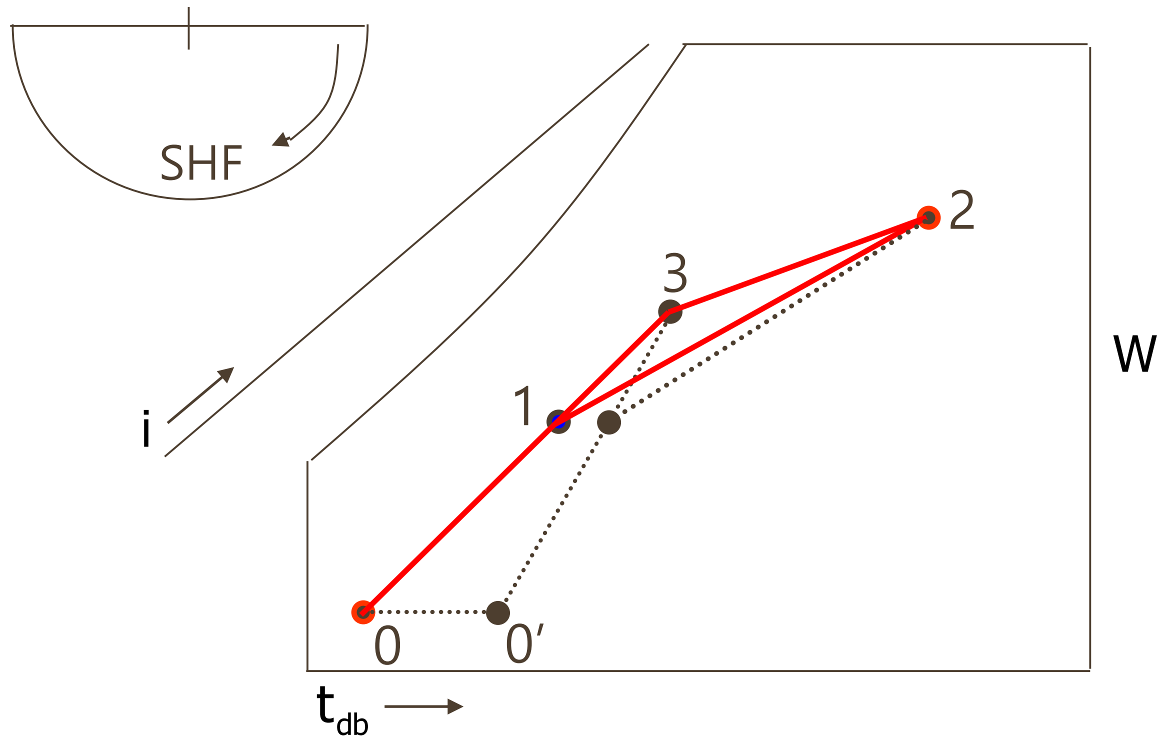
Heating system with preheat of outdoor air

Classic Moist Air Process



Psychrometric diagram for heating system with preheat of outdoor air

Classic Moist Air Process



Psychrometric diagram for heating system without preheat of outdoor air

Question and Answer Session