Energy in Buildings and Communities Programme

T-Q Chart and ω-W Chart analysis tool to describe heat and mass transfer processes in DEC/IEC process

Xiaoyun Xie, Yi Jiang

Building Energy Research Center, Tsinghua University, Beijing, China

2021. 12.21

The support from National key research and development program of China (key projects of international cooperation in science and technology innovation) (Grant number 2019YFE0102700)

Main Contents

- Some interesting questions
- T-Q chart using in heat transfer processes
- Basic heat and mass transfer processes in direct evaporative cooling(DEC) processes
- T-Q chart and ω-W Chart using for basic DEC processes
- Thermal resistance identification for basic DEC processes
- Optimization for DEC processes—from DEC to IEC
- Case study

Some interesting questions

- For DEC(direct evaporative cooling) , why the limit output air/water temperature could only be limited to inlet wet bulb temperature?
- For IEC (indirect evaporative cooling) , why the limit output air/water temperature could low to inlet dewpoint temperature?
- For IEC processes, to get much lower outlet air/water temperature, what are needed to be put in additionally compared with DEC processes?

- To think about how to build DEC/IEC processes, then design and then optimization.
- From the point of view—internal losses analysis, to find where need to be improved.

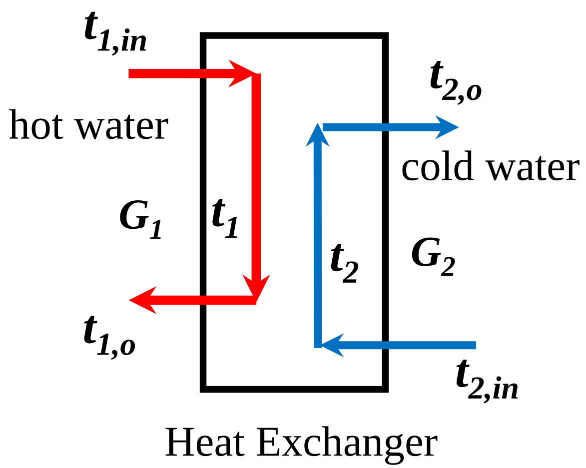
- To see the internal heat and mass transfer processes as well as the transfer losses clearly, T-Q chart and ω-W Chart could be one of the basic tools to show the heat and mass transfer processes.

T-Q chart using in heat transfer processes

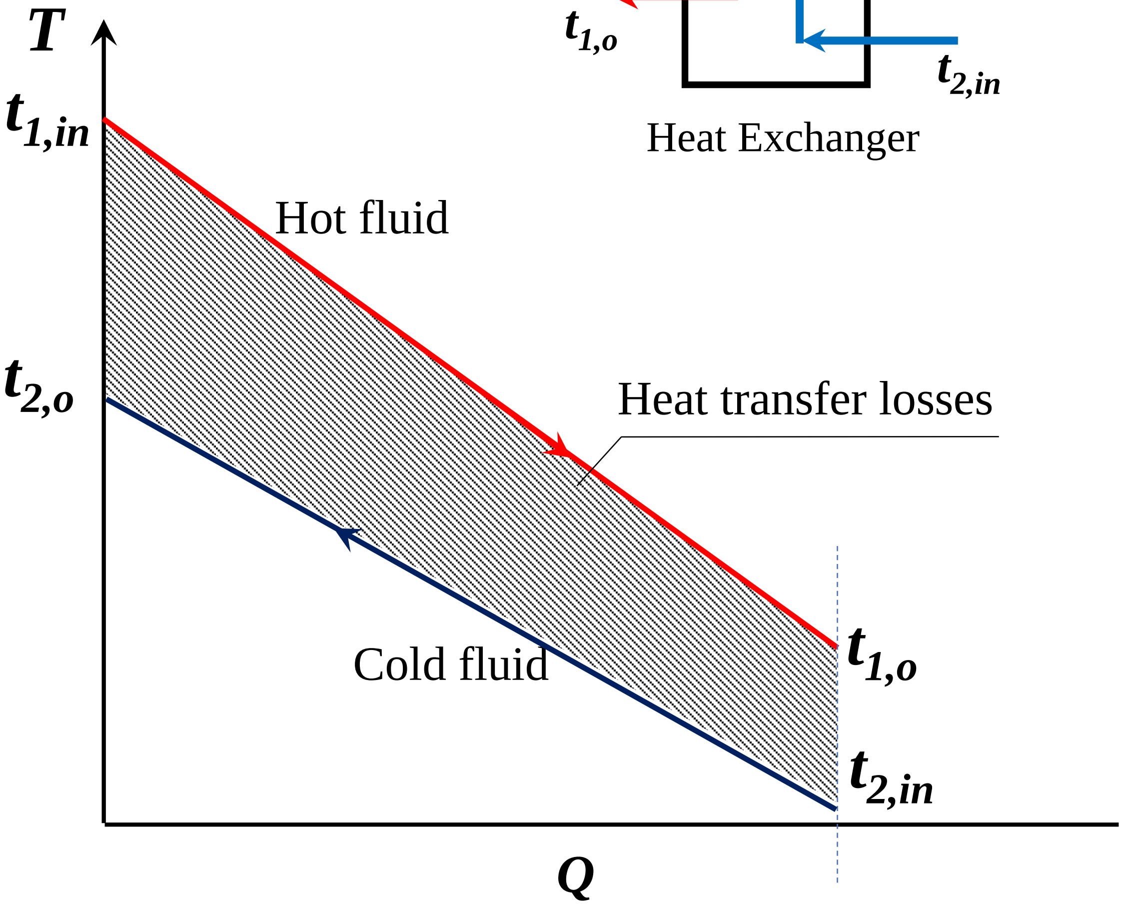
- Countercurrent heat exchangers

$$\begin{cases} G_1 c_{p1} dt_1 = KdA\,(t_2 - t_1) \\ G_2 c_{p2} dt_2 = -KdA\,(t_1 - t_2) \end{cases}$$

$$\begin{cases} \mathrm{dQ} = KdA\,(t_1 - t_2) \\ G_1 c_{p1} dt_1 = -\mathrm{dQ} \\ G_2 c_{p2} dt_2 = -dQ \end{cases} \Rightarrow \quad \frac{dt_1}{\mathrm{dQ}} = -\frac{1}{G_1 c_{p1}} \qquad \frac{dt_2}{\mathrm{dQ}} = -\frac{1}{G_2 c_{p2}}$$

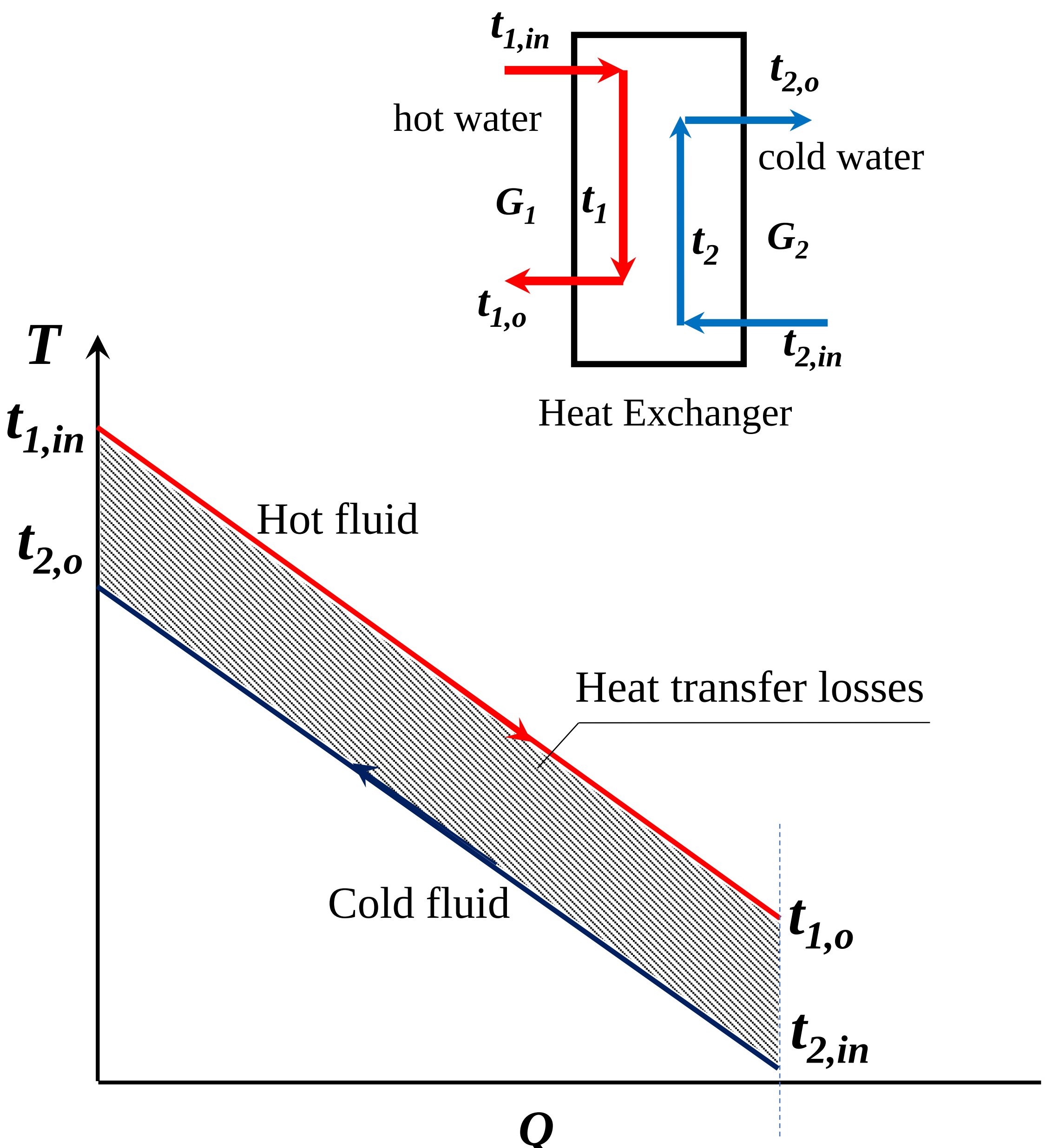


- We could draw the heat transfer process on the T-Q chart, to see the heat transfer temperature difference along with the transferred heat clearly
- The two lines represent the two fluids, to show their temperature changing with the transferred heat.
- If the flowrate and the specific heat of one side fluid is constant, the line of this fluid is a straight line, otherwise is a curve.
- The slope represents the product of the flowrate and the specific heat, the higher the slope, the lower the product.

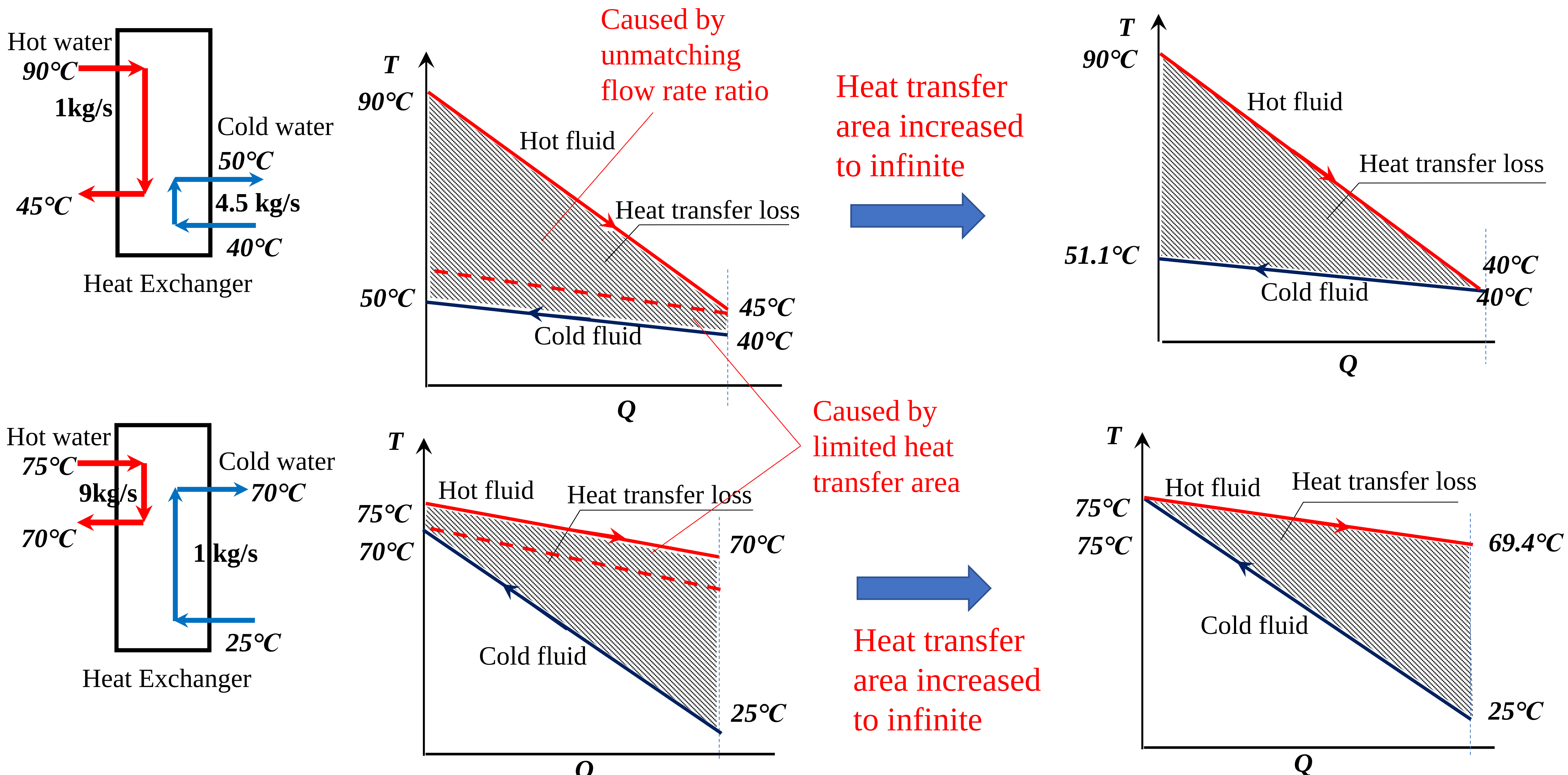


T-Q chart using in heat transfer processes

- If the two sides fluids meet: $G_1cp_1=G_2cp_2$, it is a balanced(matching) flow rate ratio.
- Along the heat transfer process, the heat transfer temperature difference is uniform.
- When the heat transfer area is increased, the temperature difference as well as the heat transfer loss is decreased.
- When the heat transfer area is infinite, the temperature difference is decreased to zero, which become a reversible heat transfer process.
- It is a matching heat transfer processes, when the two sides fluids meet flow rate matching.
- The heat transfer loss is merely due to the heat transfer area.



T-Q chart using in heat transfer processes



Unmatching performance for heat transfer processes

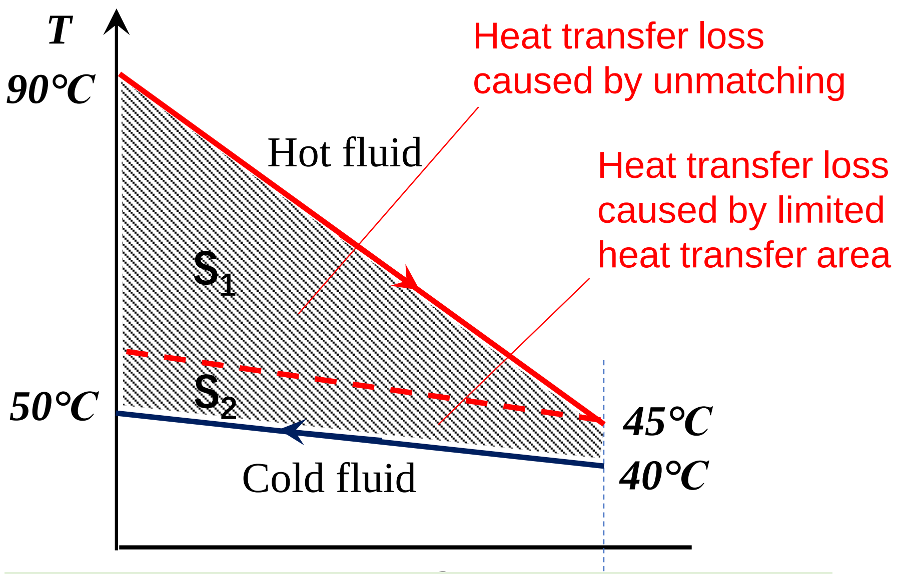
- Heat transfer loss shown in the T-Q chart, also called entransy loss

$$\triangle J_{loss} = \int_0^Q (t_1 - t_2) dQ$$

- Equivalent heat transfer resistance

$$R = \frac{\Delta J_{loss}}{Q^2} = \frac{S_1 + S_2}{Q^2} = \frac{1}{2} \cdot \frac{y_{Gcp} - 1}{G_1 c_{p1}} \cdot \frac{\exp\left(NTU_m\left(y_{Gcp} - 1\right)\right) + 1}{\exp\left(NTU_m\left(y_{Gcp} - 1\right)\right) - 1}$$

$$R = R_m + R_A$$



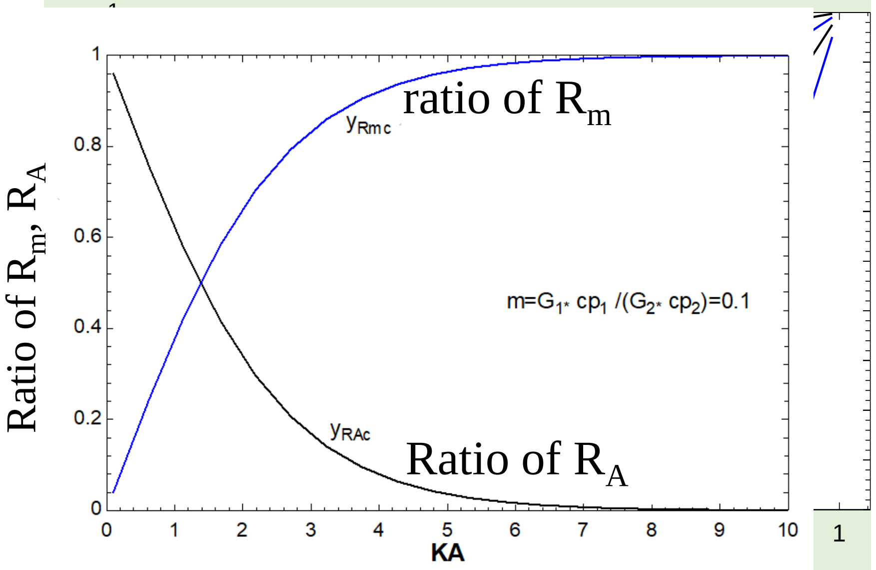
$$R_m = \frac{S_1}{Q^2} = \lim_{A \to \infty} R = \frac{1}{2} \left[\frac{1}{G_1 c_{p1}} - \frac{1}{G_2 c_{p2}}\right]$$

$$R_A = R - R_m = \frac{S_2}{Q^2} = \frac{1}{KA} \frac{NTU_m(1 - y_{Gcp})}{\exp\left(-NTU_m(y_{Gcp} - 1)\right) - 1} = \frac{1}{KA} \cdot a$$

R_m: heat transfer resistance caused by unmatching flow rate ratio

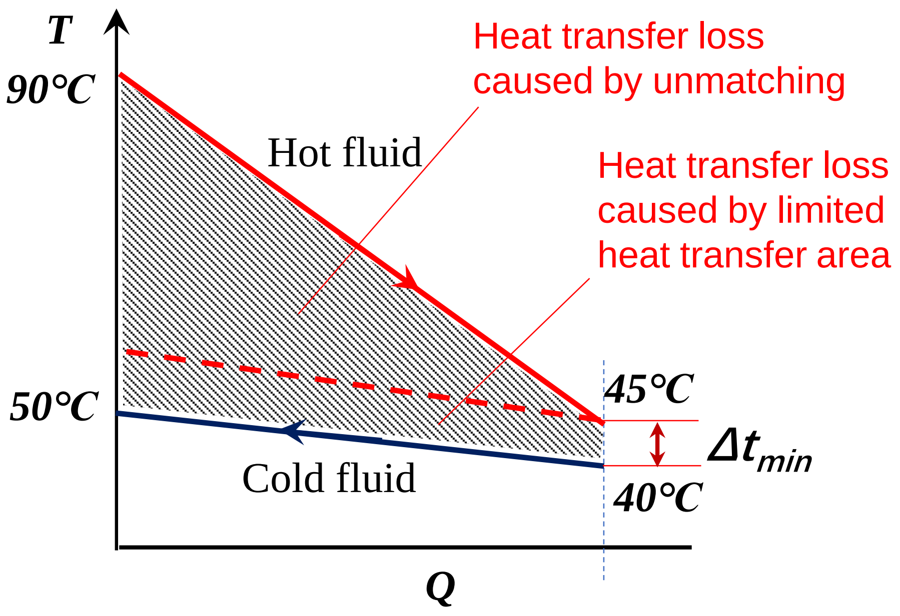
R_A: heat transfer resistance caused by limited heat transfer area

$$y_{Gcp} = \frac{G_1 c_{p1}}{G_2 c_{p2}} \qquad G_1 cp_1 < G_2 cp_2$$



T-Q chart using in heat transfer processes

- For heat transfer processes, the equivalent heat transfer resistance could be used :
  - To analyze the principal contradiction—the unmatching flow rate ratio, or limited heat transfer area?
  - To optimize the heat transfer network, using some possible rules due to the resistance analysis, such as
    - uniform of heat transfer resistance of each heat transfer process
    - uniform of unmatching heat transfer resistance of each heat transfer process



$$R = R_m + R_A$$

$$R_m = \lim_{A\to\infty} R = \frac{1}{2}\left[\frac{1}{G_1 c_{p1}} - \frac{1}{G_2 c_{p2}}\right]$$

$$R_A = \mathrm{R} - R_m = \frac{S_2}{Q^2} = \frac{1}{KA}\frac{NTU_m(1-y_{Gcp})}{\exp\left(-NTU_m(y_{Gcp}-1)\right)-1} = \frac{1}{KA}\cdot a$$

For evaporative cooling processes……

Basic process of evaporative cooling

- For countercurrent water-air direct contact heat and mass transfer processes,

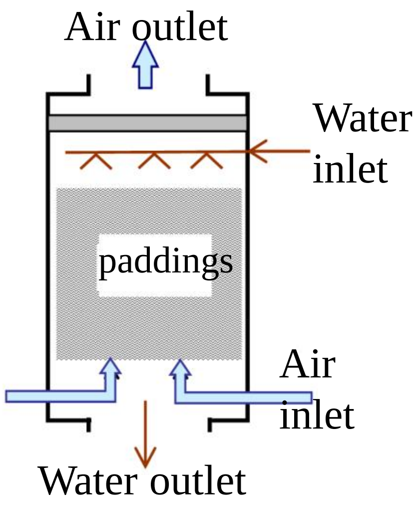
$$G_a c_{pa} dt_a = -K_s dA\,(t_w - t_a)$$

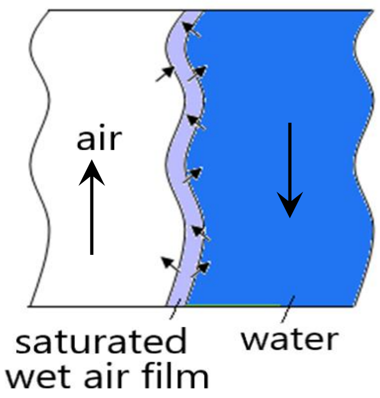
$$G_a d\omega_a = -K_d dA(\omega_{wa} - \omega_a)$$

$$G_w c_{pw} dt_w = K_s dA(t_a - t_w) + r_0 K_d dA(\omega_a - \omega_{wa})$$

$$dW = K_d dA(\omega_{wa} - \omega_a)$$

Where k_s represents the heat transfer coefficient between water and air, k_d represents the mass transfer coefficient between water and air, r_0 represents the latent heat of water vaporization, ω represents air humidity ratio(g/kg.air) .





- Heat transfer process and mass transfer process coupled with each other.
- Using T-Q chart and ω-W chart to see heat transfer and mass transfer and their relation clearly.

Basic assumptions:

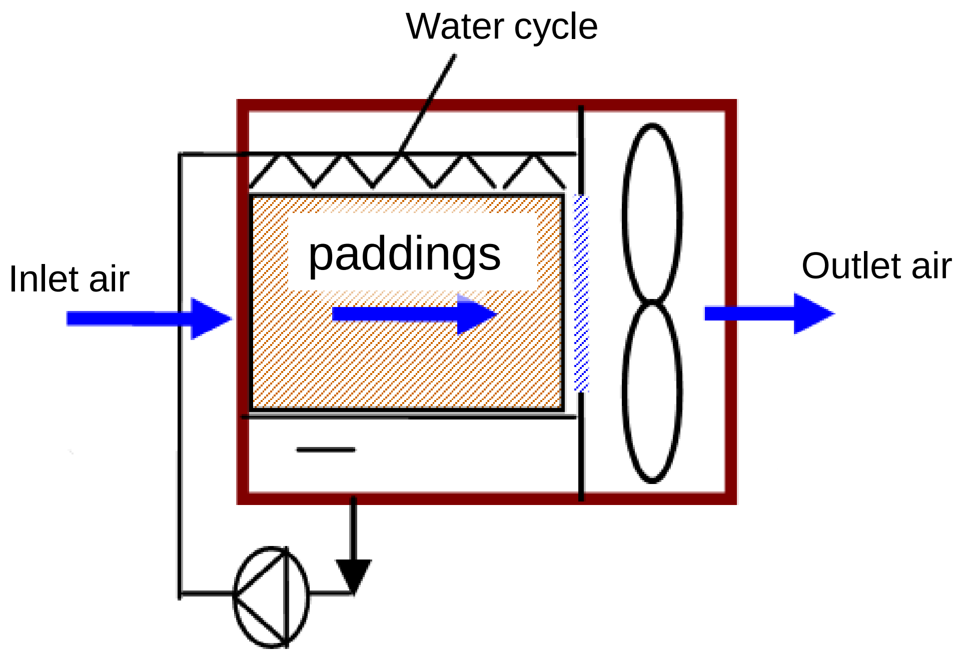
- **All the latent heat for water evaporation coming from water**
- **Lewis number is approximately 1.**

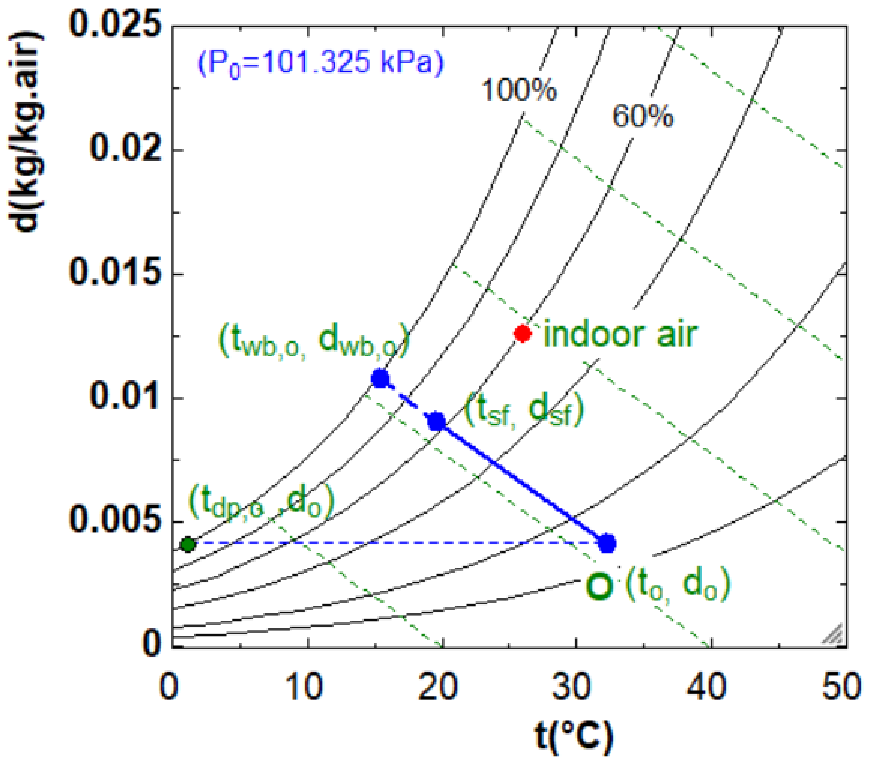
Basic understanding

- **Heat transfer process, mass transfer process, water evaporation process occur at the same time.**
- **Heat transfer process occurs between air and water, with temperature difference;**
- **Mass transfer process occurs between air and water, with humidity ratio difference;**
- **Water evaporation process occurs in the saturated wet air film, reversible process.**

Using T-Q chart and ω-W chart to analysis evaporative cooling process

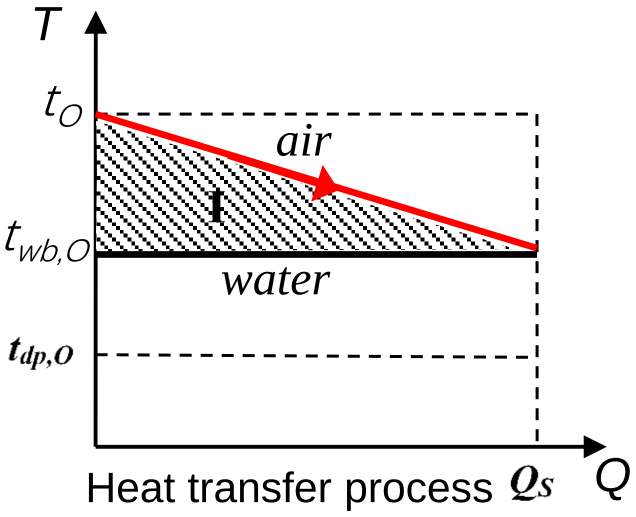
- Take two processes for example
- **Case1:** for direct evaporative air cooling process, inlet air and the saturated air of water are at the same isoenthalpy line.
  - Outlet limit air temperature is inlet wet bulb temperature, why it could not be low to inlet dewpoint temperature?

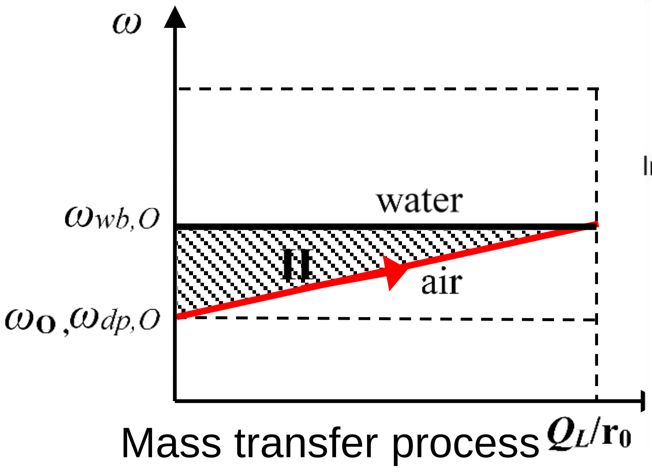


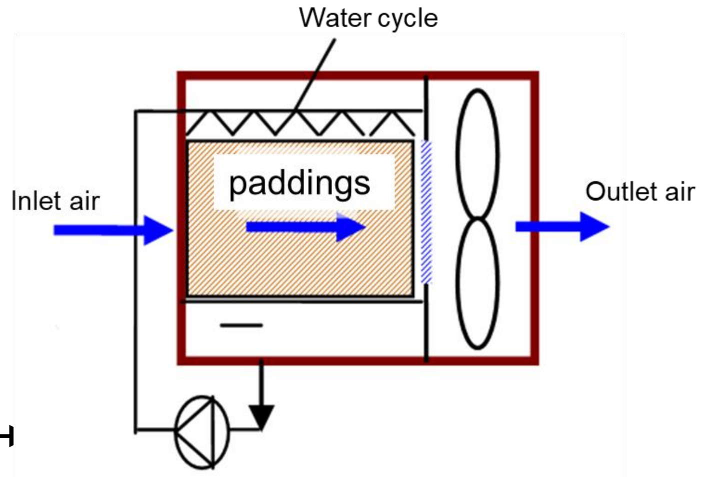


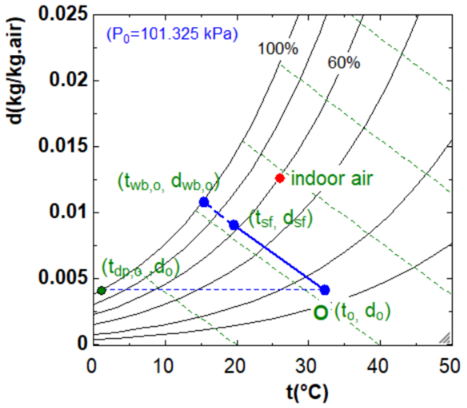
Using T-Q chart and ω-W chart for internal losses analysis

- **Case1:** for direct evaporative air cooling process
- For heat and mass transfer processes





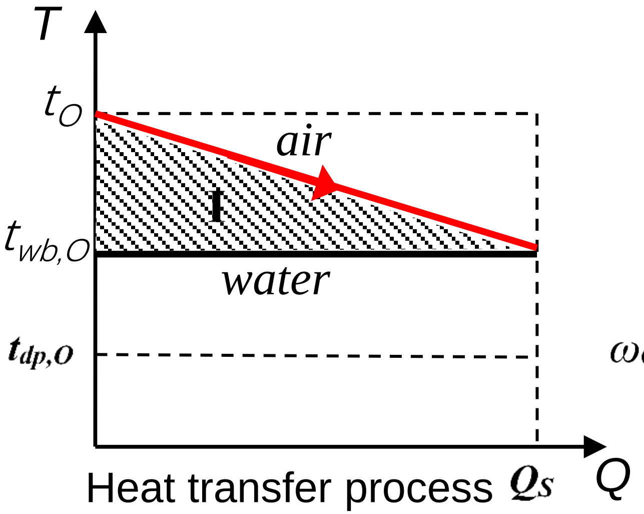


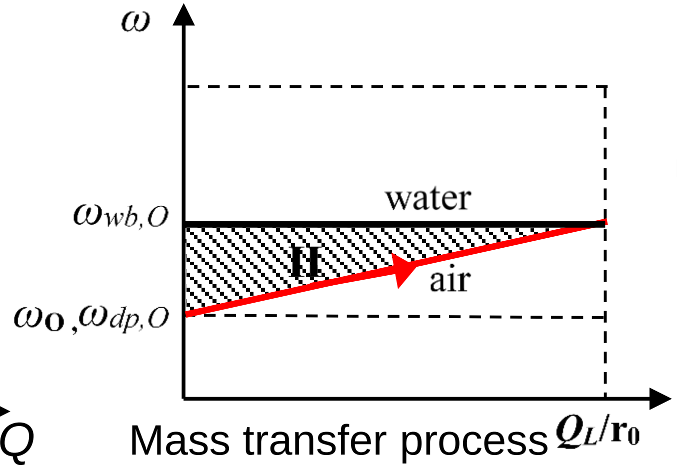


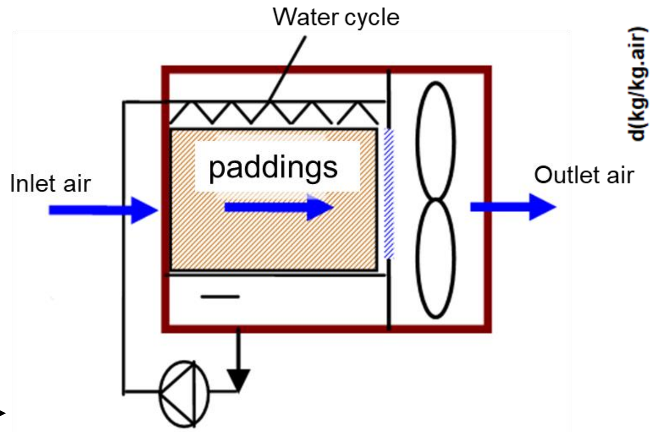
- In T-Q chart, air transfers heat to water, it is an unmatching heat transfer process. However, the loss could not be avoided at any flowrate ratio, including matching flowrate ratio. The loss is not caused by unmatching flowrate ratio design.
- In ω-W chart, water transfers moisture to air, it is also an unmatching mass transfer process, which could not be avoided by matching flowrate design neither.
- **Air transfer heat to water, while water transfer moisture to air, the directions of heat transfer and mass transfer are opposite.** The losses of heat transfer and mass transfer could not be avoided at any air-water flow rate ratio or even if the heat and mass transfer area is increased to infinite.
- It is unmatching evaporative cooling process, not caused by unbalanced flow rate ratio, but caused by the inlet conditions of air and water, called **parameter unmatching processes.**

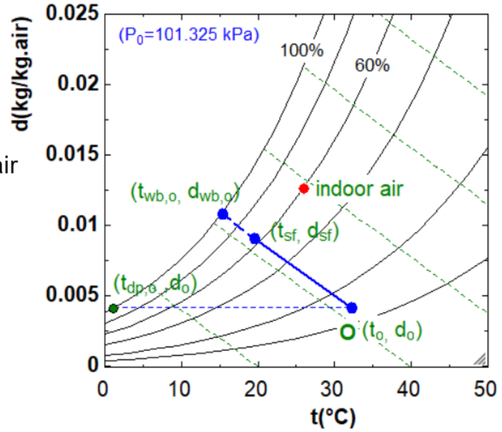
Using T-Q chart and ω-W chart for internal losses analysis

- **Case1:** for direct evaporative air cooling process
- For heat and mass transfer processes









- Area I is the heat transfer loss shown in the T-Q chart, we could call it heat transfer entransy dissipation;
- Area II is the mass transfer loss shown in the ω-W chart, we could call it mass transfer entransy dissipation;

$$\triangle J_{s,loss}=\int_0^{Q_s}\Delta t dQ_s$$

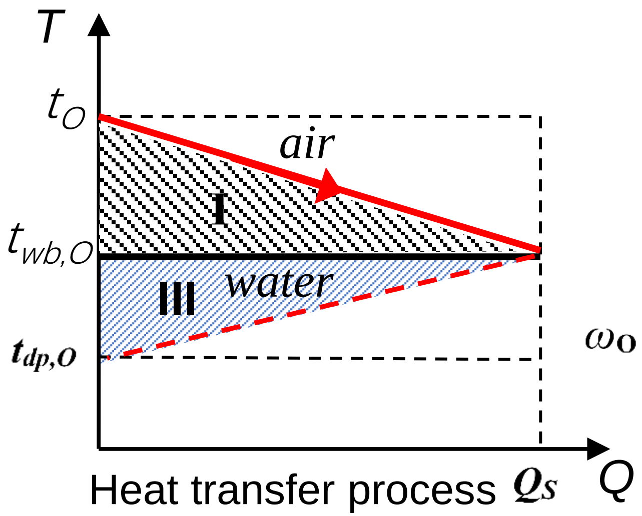
Where Q_s represents the transferred sensible heat, Δt represents the heat transfer temperature difference

$$\triangle J_{d,loss}=\int_0^{W}\Delta\omega dW$$

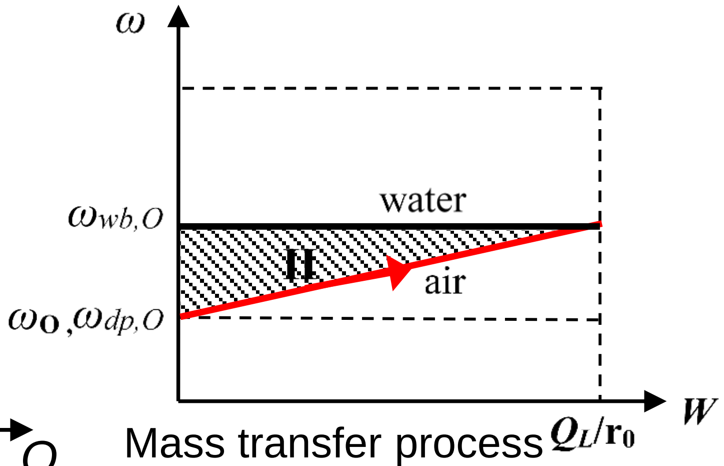
Where W represents the transferred moisture, Δω represents the humidity ratio difference for mass transfer

Using T-Q chart and ω-W chart for internal losses analysis

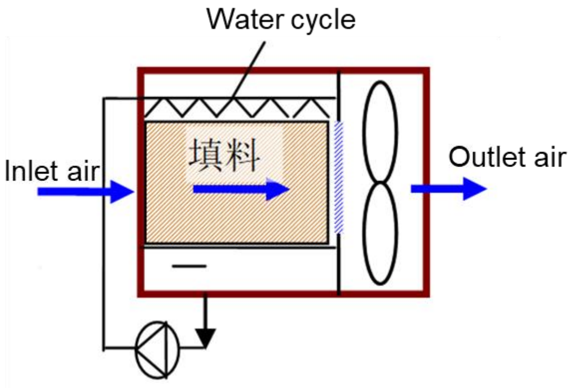
- For heat and mass transfer processes

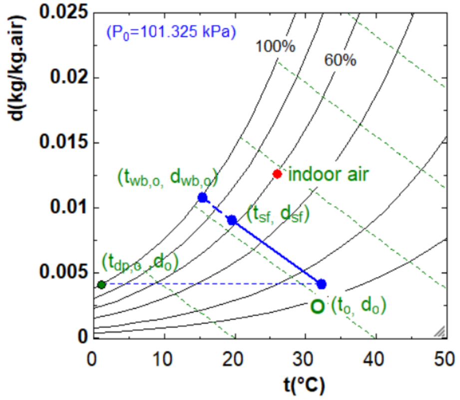


Heat transfer process



Mass transfer process





Where ω represents air humidity ratio(g/kg.air)

- **If we assumed the saturation line between the wet bulb temperature and dew point temperature is linear, where on this part or saturation line,** ω=a*t+b**, we could get the equivalent mass transfer loss (area II) in the T-Q chart, as shown as area III.**

$$dW = -G_a d\omega_a = -aG_a dt_{a,dp}$$

$$Lewis = \frac{k_s}{k_d c_{pa}} = 1$$

$$Area_{II} = \int_0^{Q_L/r_0} (\omega_W - \omega_a) dW$$

$$= \int_{t_{wb,O}}^{t_{dp,O}} -a^2 G_a (t_W - t_{a,dp}) dt_{a,dp}$$

$$= \frac{1}{2} a^2 G_a (t_{wb,o} - t_{dp,o})^2 = \frac{a}{r_0} Area_{III}$$

For this case,

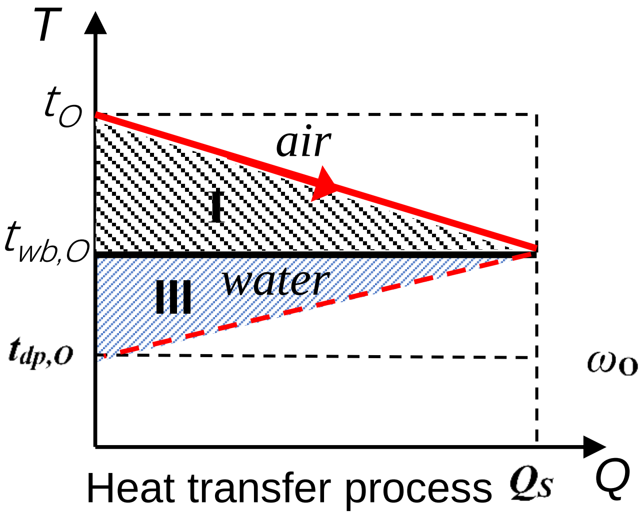
$$Q_L = Q_S$$

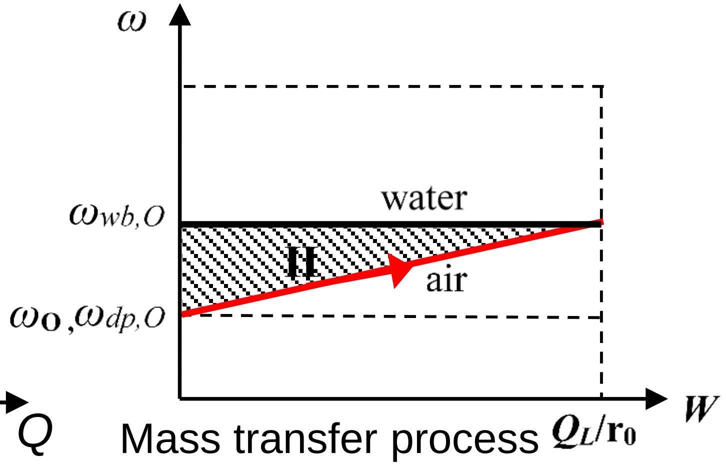
Q_L is latent heat of transferred moisture;
Q_s is transferred sensible heat

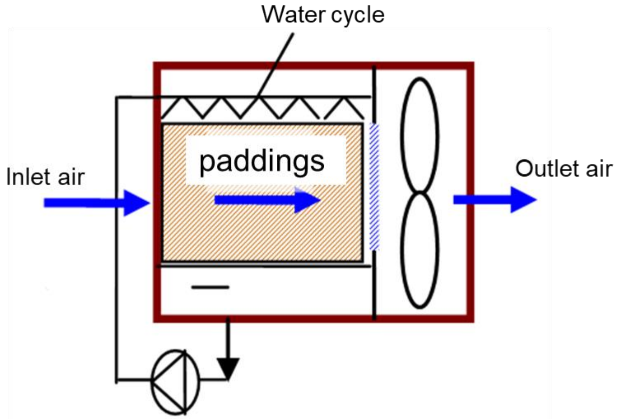
Where r_0/a represents a conversion factor between heat transfer loss and mass transfer loss

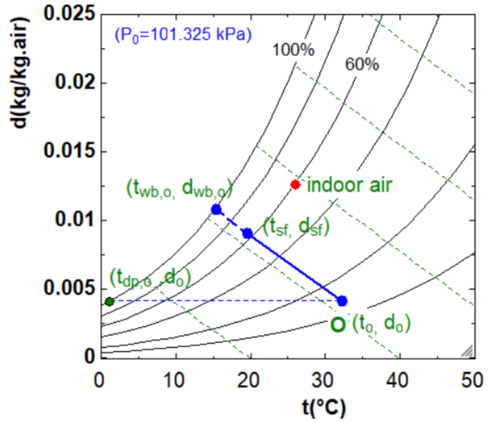
Using T-Q chart and ω-W chart for internal losses analysis

- For heat and mass transfer processes







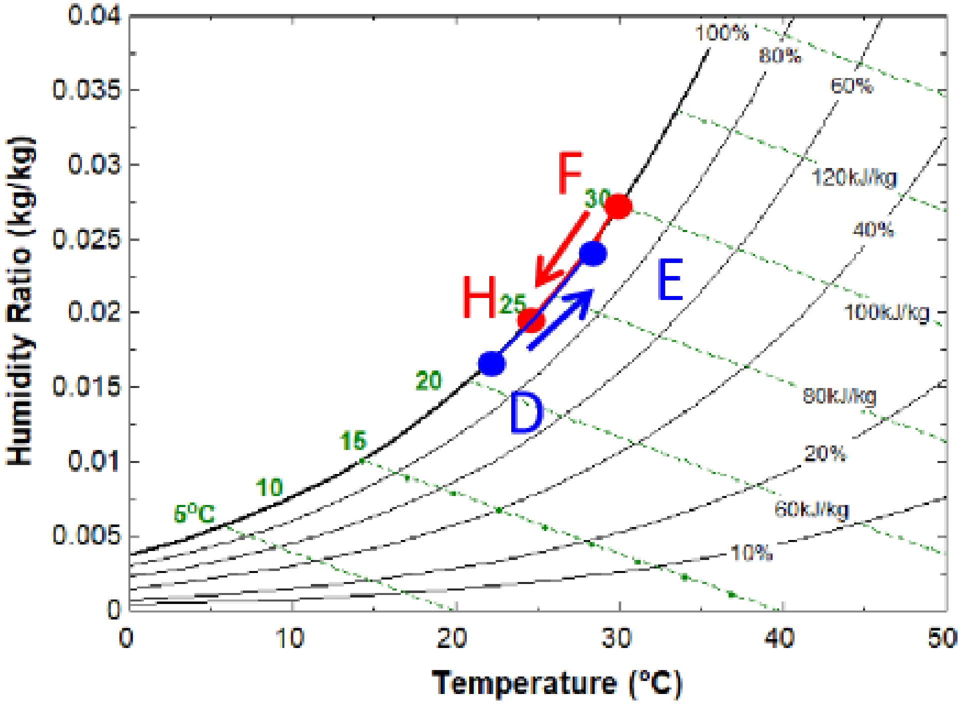


Where ω represents air humidity ratio(g/kg.air)

- **Thus, we could give the reason why the limit temperature of direct evaporative cooling process could only be inlet wet bulb temperature, it is because the heat grade at inlet dew point temperature is lost by mass transfer processes.**
- **To get the cooling source with inlet dew point temperature, it is better to avoid opposite heat and mass transfer processes, that is to design matching evaporative cooling process.**

Using T-Q chart and ω-W chart to analysis evaporative cooling process

- **Case2：For direct evaporative cooling process, if the inlet air is at the saturation line:**
  - Air is heated and humidified, from D to E
  - Water is cooled, from F to H



- Matching flow rate ratio of air and water is designed:
  - Equivalent specific heat of air is defined, as $c_{p,ea}$
  - Matching flow rate ratio, $\boxed{m = 1}$

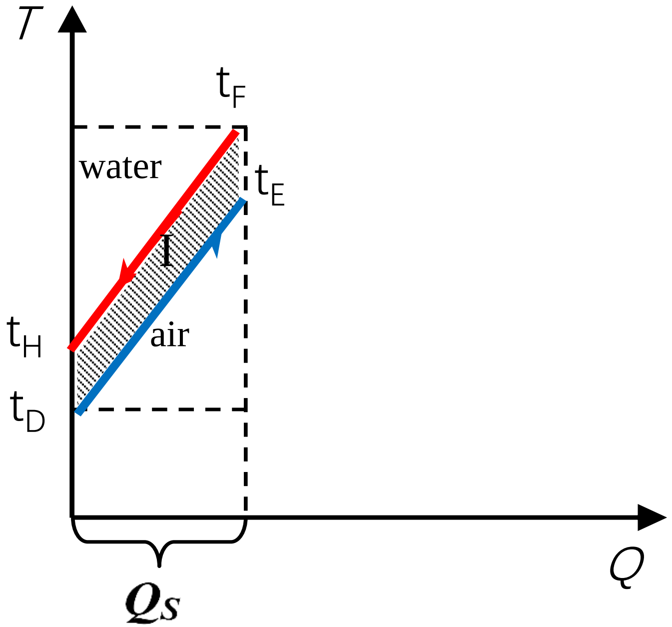
$$m = \frac{G_a \cdot c_{p,ea}}{G_w \cdot c_{pw}}$$

$$c_{p,ea} = \frac{dh_{ea}}{dt_{ea}} = \frac{h_E - h_D}{T_E - T_D} = c_{pa} + r_0 \cdot \frac{\Delta\omega}{\Delta T}$$

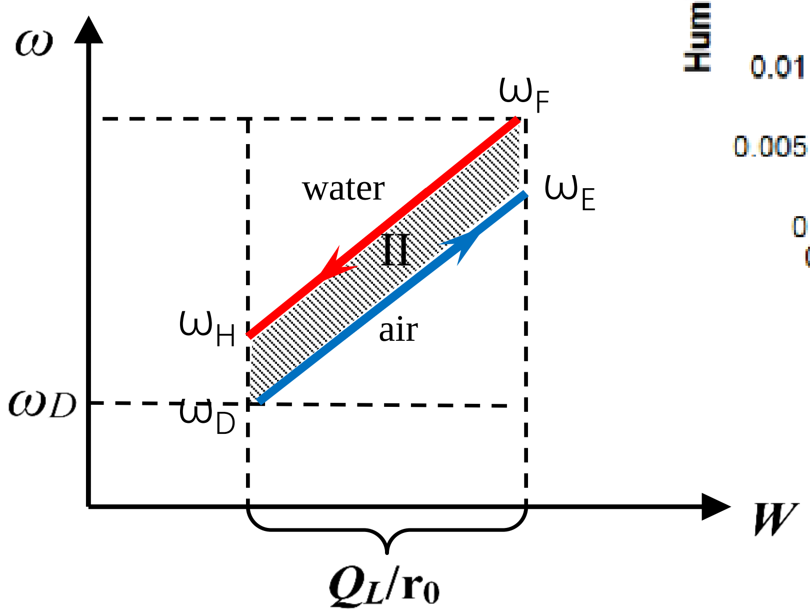
Using T-Q chart and ω-W chart to analysis evaporative cooling process

- For direct evaporative cooling process, if the inlet air is at the saturation line:
  - Air is heated and humidified, from D to E
  - Water is cooled, from F to H

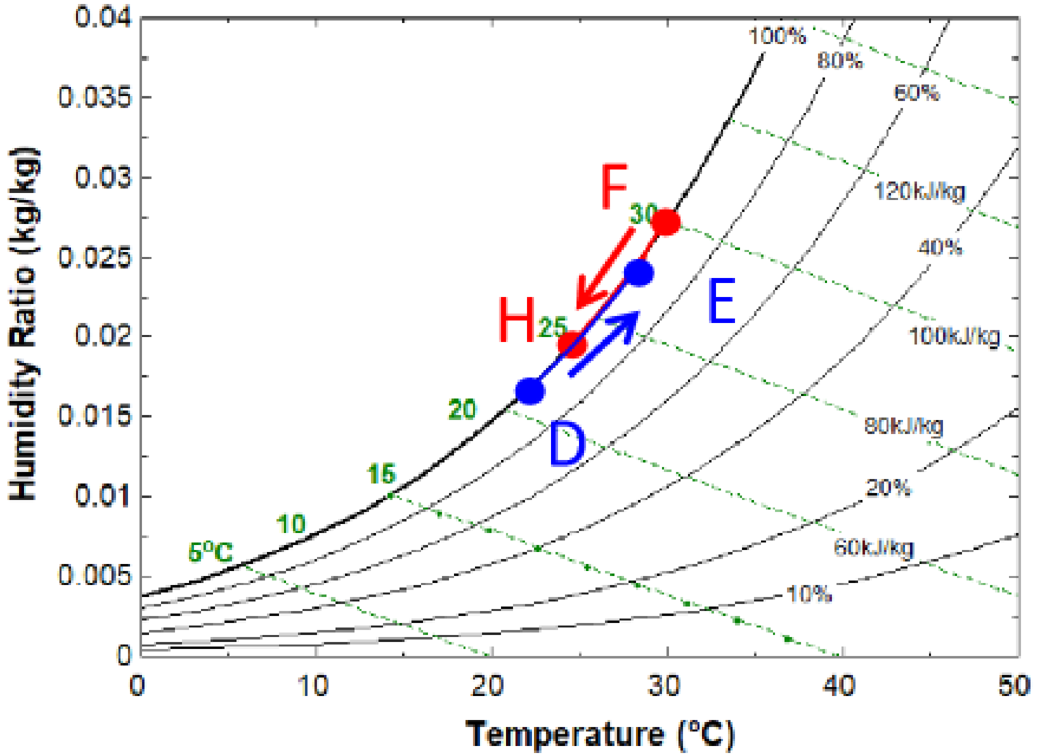
- When matching flow rate ratio of air and water is designed, the heat and mass transfer process is shown in T-Q chart and ω-W chart,



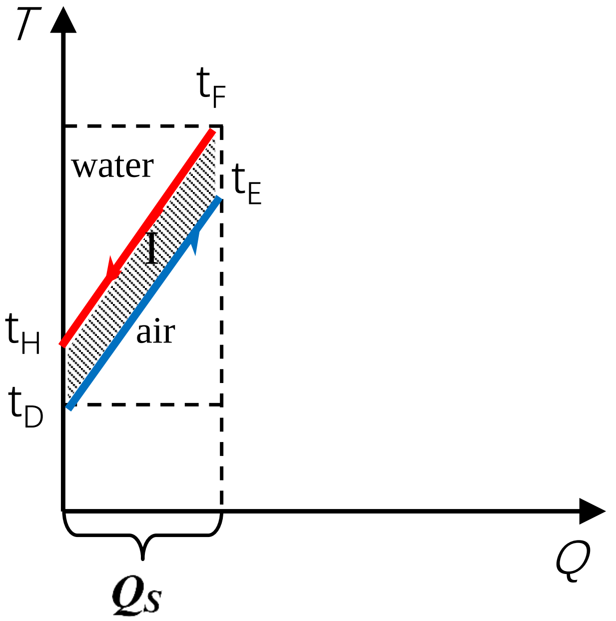
Heat transfer process



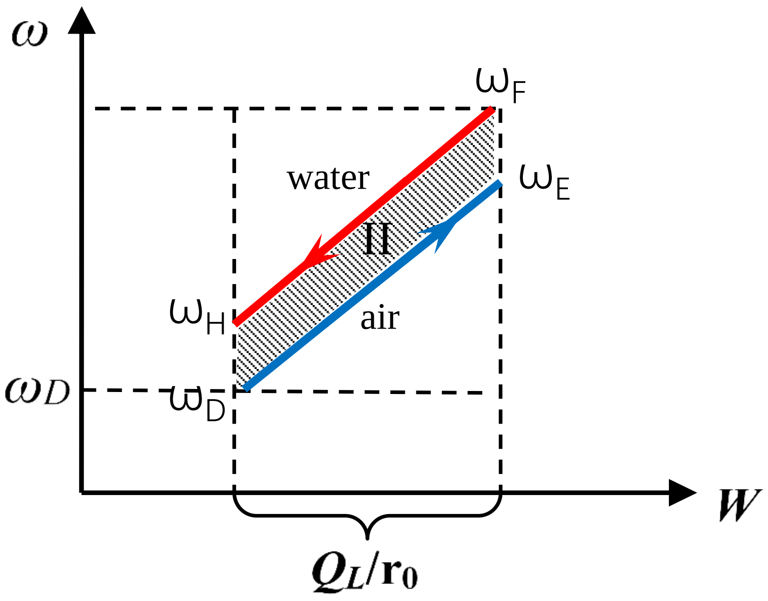
Mass transfer process



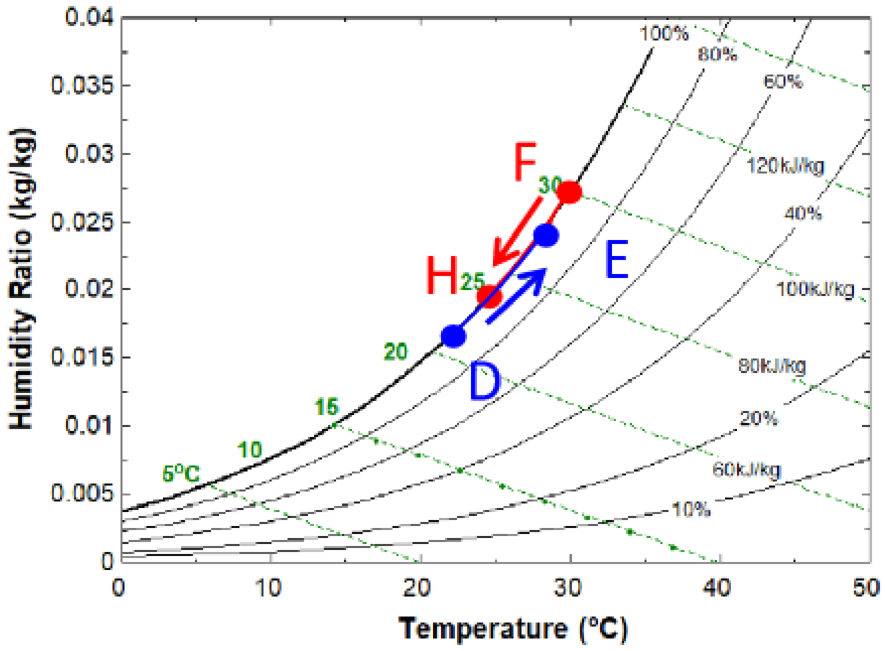
Using T-Q chart and ω-W chart for internal losses analysis



Heat transfer process



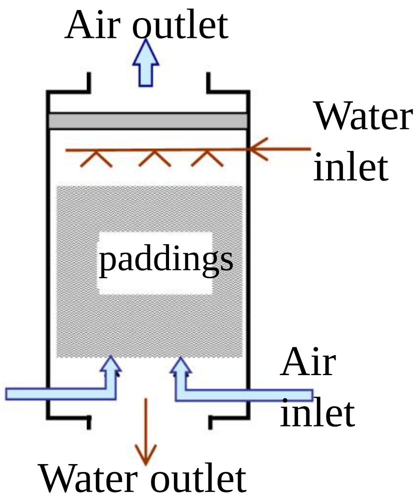
Mass transfer process

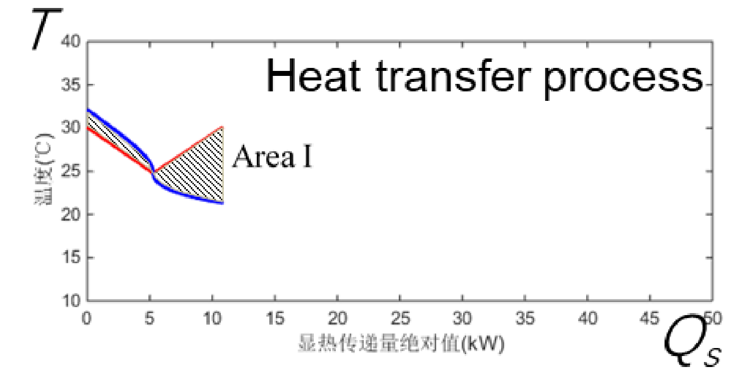


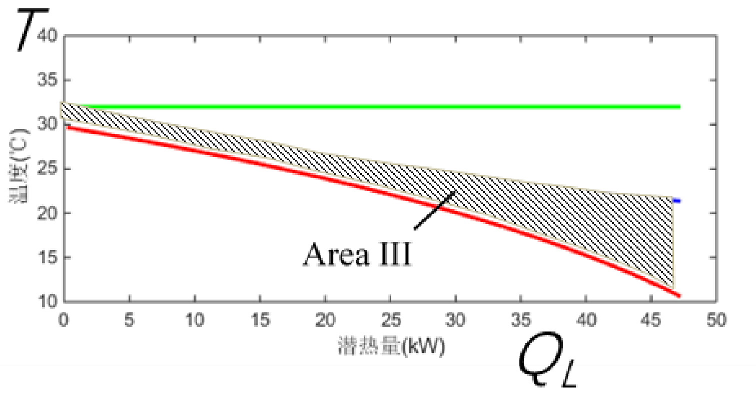
- For direct evaporative cooling process, the inlet air is at the saturation line, and the matching flow rate ratio is designed
  - Water transfers heat to air, and water transfer moisture to air, **the transfer direction for heat and moisture is the same.**
  - **The grade loss of heat transfer and mass transfer,** or so called entransy dissipation, shown as Area I and Area II, **could be reduced to zero by increasing the heat and mass transfer area.**
  - **This is because the inlet air is at the saturation line for a direct evaporative cooling process, we called it parameter matching.**

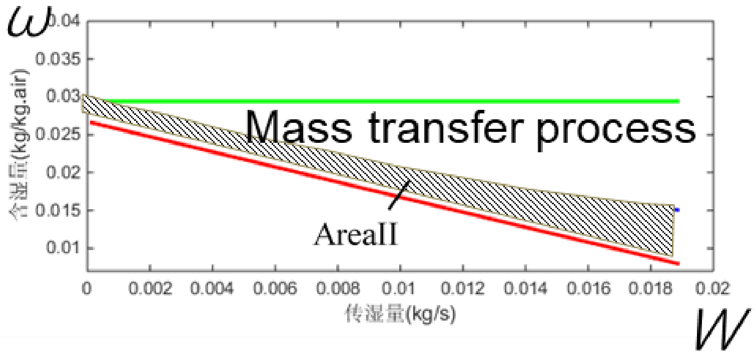
Using T-Q chart and ω-W chart to analysis evaporative cooling process

- Common countercurrent cooling tower processes

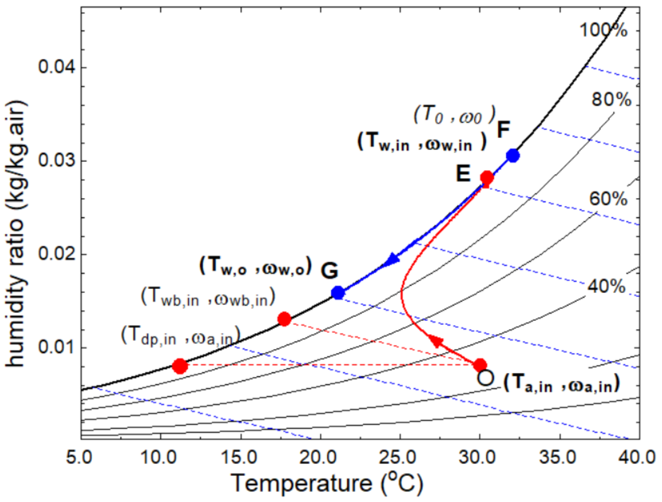








Area III, equivalent entransy dissipation of mass transfer (Area II) in T-Q chart



- For heat transfer process, the direction changed along the whole process
- For the upper part of the padding, the direction of heat transfer and mass transfer are the same, while for the lower part, the direction is opposite.
- The limit outlet water temperature could only be inlet wet bulb temperature, due to the mass transfer loss.
- Flow rate between air and water could be matched;
- While inlet air is far from saturation line, inlet parameter unmatching.

Matching Evaporative cooling progress

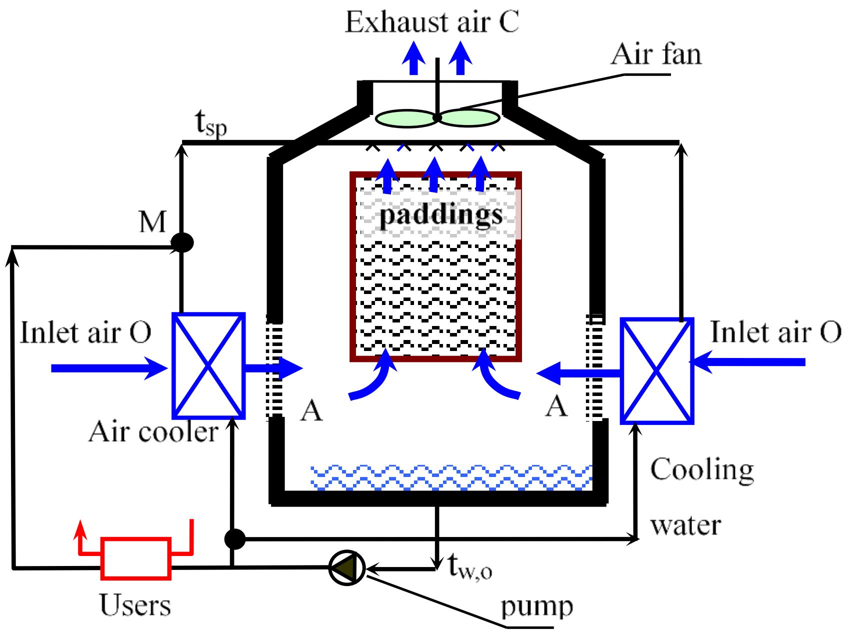
- **Matching Evaporative cooling process is thus identified to meet the following three conditions:**
  - Inlet parameter matching, the inlet air is at the saturation line.
  - Flow pattern matching, countercurrent heat and mass transfer;
  - Flow rate matching, $$m = \frac{G_a \cdot c_{p,ea}}{G_w \cdot c_{pw}} = 1$$

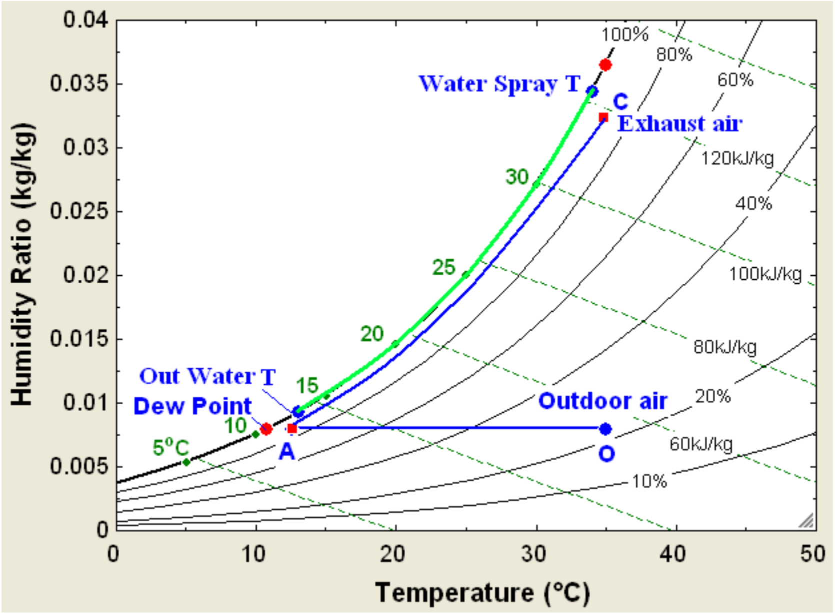
- **The optimization direction of the evaporative cooling processes design:**

To make the inlet air of direct evaporative cooling process to be at or near the saturation line, to realize inlet parameter matching.

From DEC to IEC……

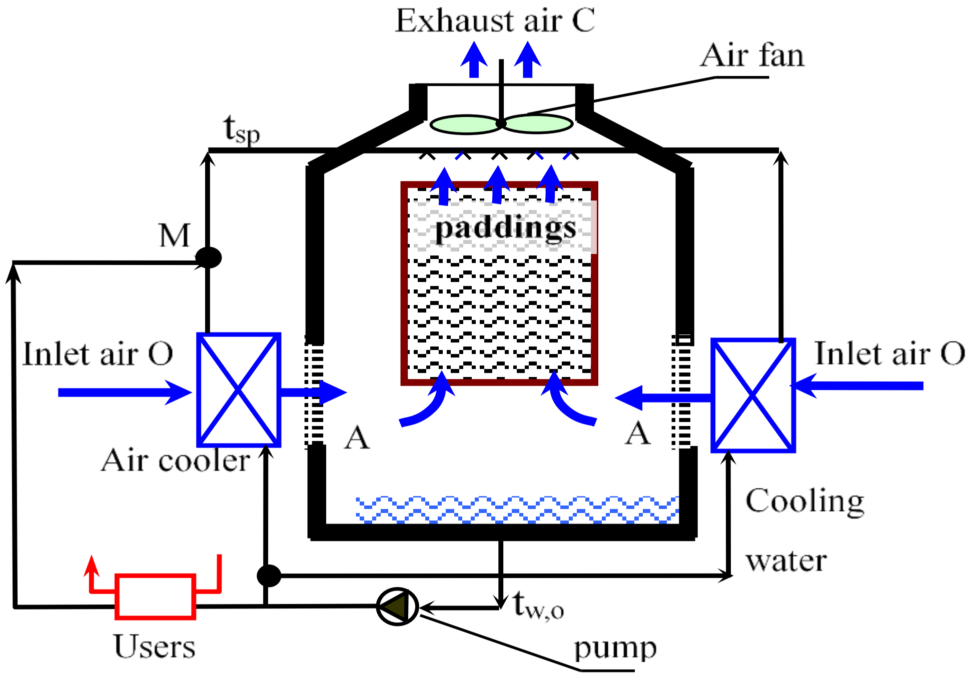
- Indirect evaporative water chiller

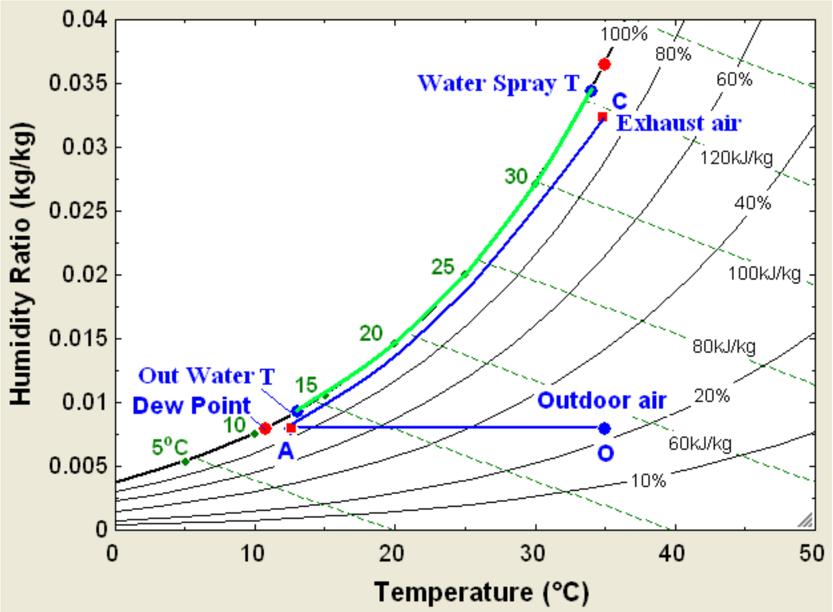




- **Key processes:**
  - **Inlet parameter matching design:** to cool the inlet air to make it near the saturation line through a countercurrent air cooler by part of the produced cooling water;
  - **Flow pattern matching design:** to produce cold water by a countercurrent padding tower;
  - **Flow rate matching design** for each of the heat transfer or heat and mass transfer process.

Indirect Evaporative water chiller process





- Matching flow rate:

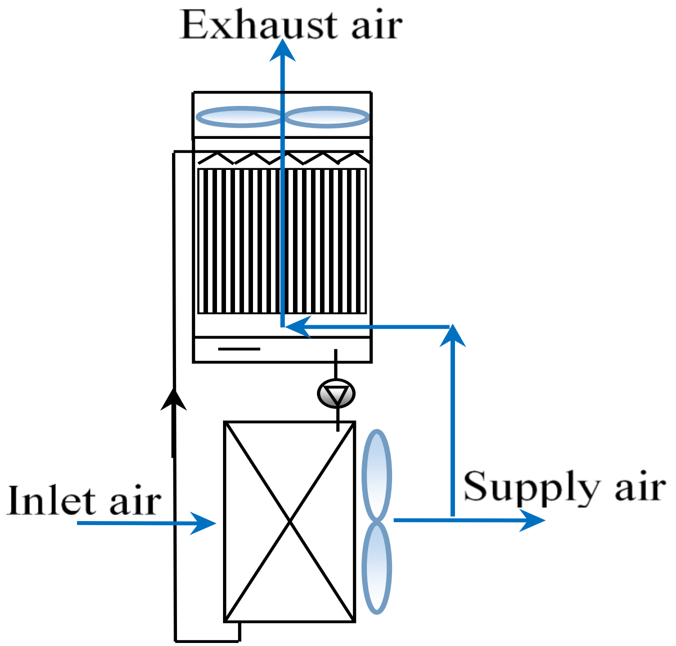
For air cooler, $G_{w1}c_{pw} = G_a c_{pa}$

For cooling tower, $(G_{w1}+G_w)c_{pw} = G_a c_{pea}$

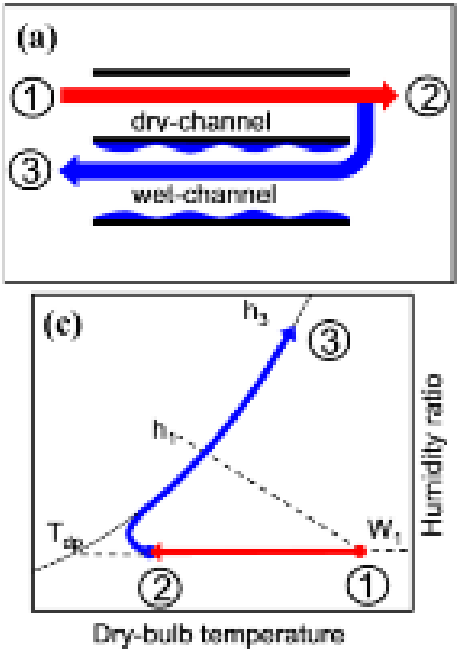
Where G_w is the cold water flow rate supply to users, G_{w1} is the cold water flow rate supply to air cooler.

It is proved that, when the heat and mass transfer area is increased to infinite, the limit out water temperature could be close to dew point temperature of inlet air, with very low temperature difference caused by non-linear of the saturation line.

- Indirect Evaporative air coolers



External IEC coolers with one part of supply air as secondary air



M-Cycle IEC air coolers

These two kinds of indirect evaporative cooling processes to produce cooling air could also be matching evaporative processes, if the flow rate ratio is matching designed, using countercurrent heat and mass transfer processes, and to have enough heat transfer area for the inlet air to be cooled near the saturation line.

Using T-Q chart and ω-W chart for internal losses analysis

- The identification of equivalent thermal resistance of evaporative cooling process considering both heat transfer and mass transfer processes.

$$R_H = \frac{\int_0^{Q_s} \Delta t \, dQ_s + \int_0^{W} (\alpha \Delta\omega) dW}{{Q_w}^2}$$

$$\alpha = \frac{r_0}{a} \qquad a = \frac{d\omega}{dt}, at\ the\ saturation\ line$$

Where Q_w represents the cooling energy of water side;

Q_s represents the transferred sensible heat, Δt represents the heat transfer temperature difference

W represents the transferred moisture, Δω represents the humidity ratio difference for mass transfer

If the saturation line for the working conditions of one evaporative cooling process could be assumed to be linear, thus the equivalent thermal resistance could be

$$R_H = \frac{\alpha \Delta J_{d,loss} + \Delta J_{s,loss}}{{Q_w}^2}$$

$$\triangle J_{s,loss} = \int_0^{Q_s} \Delta t dQ_s$$

$$\triangle J_{d,loss} = \int_0^{W} \Delta\omega dW$$

Thermal resistance analysis for evaporative cooling processes

- The total equivalent thermal resistance

$$R_H = \frac{\alpha \Delta J_{d,loss} + \Delta J_{s,loss}}{Q_w^{\ 2}}$$

- If the flow rate ratio of evaporative cooling process meets flow rate matching, countercurrent flow, the total equivalent thermal resistance could be deducted as:

$$\mathrm{m} = \frac{G_a \cdot c_{p,ea}}{G_w \cdot c_{pw}}$$

$$R_H = \frac{1}{k_s (c_{p,ea} / c_{pa}) A} + \frac{1}{2} \cdot \frac{1}{G_a c_{p,ea}} \cdot \frac{c_{pa}}{r_0 a} \cdot \frac{(1 + k_s A / (G_a c_{pa}))^2}{[k_s A / (G_a c_{pa})]^2} \cdot \frac{e^{2k_s A/(G_a c_{pa})} - 1}{e^{2k_s A/(G_a c_{pa})}} \cdot \frac{(T_{a,in} - T_{sa,in})^2}{(T_{w,in} - T_{sa,in})^2}$$

- Unmatching thermal resistance:

$$R_{H,m} = \lim_{kA \to \infty} R_H$$

$$R_{H,m} = \lim_{kA \to \infty} R_H = \frac{1}{2} \cdot \frac{1}{G_a c_{pea}} \cdot \frac{c_{pa}}{r_0 a} \cdot \frac{(T_{a,in} - T_{sa,in})^2}{(T_{w,in} - T_{sa,in})^2}$$

Caused by unmatching inlet parameter of water and air ,not by flow rate ratio

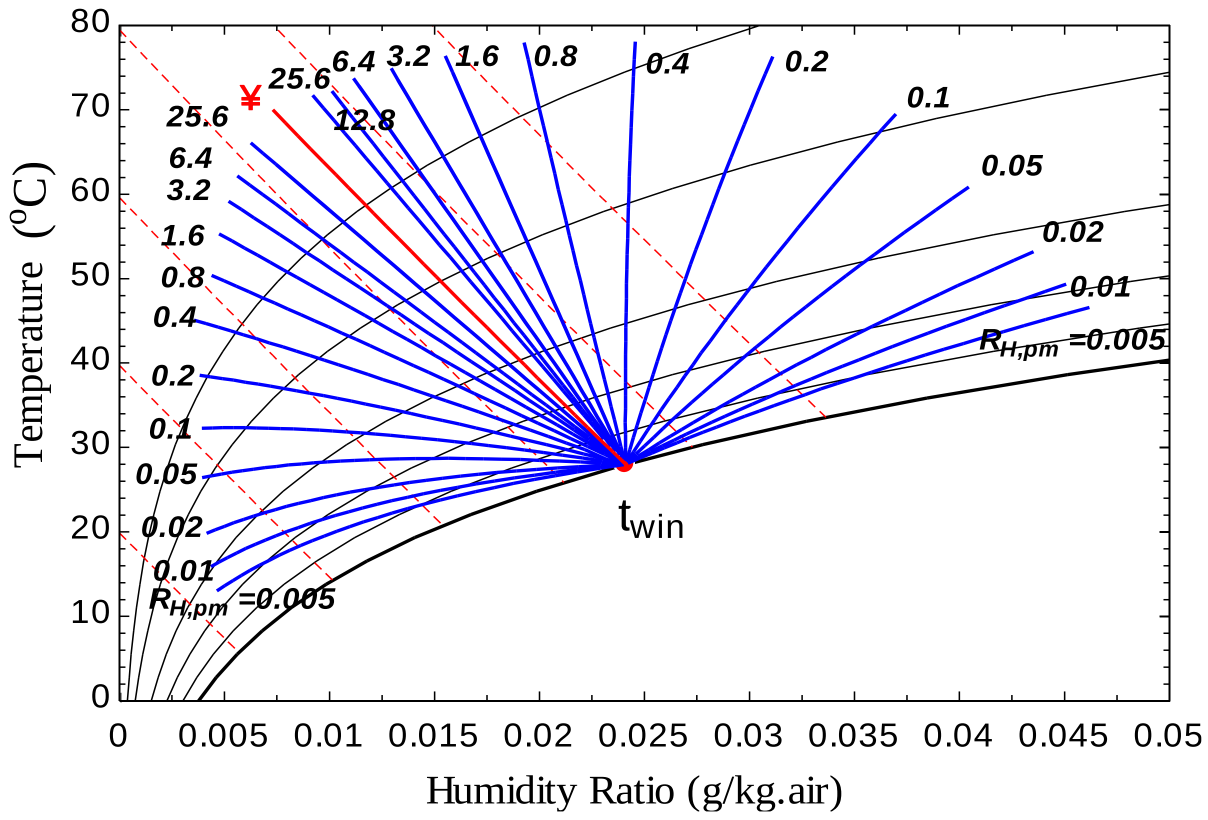
- The left thermal resistance—thermal resistance caused by finite heat transfer area:

$$R_{H,f} = R_H - R_{H,m}$$

Thermal resistance analysis for evaporative cooling processes

- **When flow rate ratio matched,**
- **Unmatching thermal resistance** caused by **unmatching inlet parameter of water and air**

$$R_{H,m} = \lim_{kA\to\infty} R_H = \frac{1}{2}\cdot\frac{1}{G_a c_{pea}}\cdot\frac{c_{pa}}{r_0 a}\cdot\frac{(T_{a,in}-T_{sa,in})^2}{(T_{w,in}-T_{sa,in})^2}$$



iso-inlet parameter unmatching thermal resistance

- If inlet air is at the saturation line, the unmatching inlet parameter thermal resistance is equal to zero;
- If inlet air is at the iso-enthalpy line of inlet water, the inlet parameter unmatching thermal resistance is infinite;
- Compared with DEC processes, IEC processes are aimed to reduce inlet parameter unmatching thermal resistance.

Thermal resistance analysis for evaporative cooling processes

- **When air-water flow rate ratio is matched,**
- **Thermal resistance caused by finite heat transfer area**

$$R_{H,f}=R_H-R_{H,m}=\frac{1}{k_s(c_{p,ea}/c_{pa})A}+R_{H,m}\cdot\left[\frac{(1+k_sA/(G_ac_{pa}))^2}{[k_sA/(G_ac_{pa})]^2}\cdot\frac{e^{2k_sA/(G_ac_{pa})}-1}{e^{2k_sA/(G_ac_{pa})}}-1\right]$$

$$R_{H,m}=\lim_{kA\to\infty}R_H=\frac{1}{2}\cdot\frac{1}{G_ac_{pea}}\cdot\frac{c_{pa}}{r_0a}\cdot\frac{(T_{a,in}-T_{sa,in})^2}{(T_{w,in}-T_{sa,in})^2}$$

- **When inlet air at the saturation line**

$$R_{H,f}=\frac{1}{k_s(c_{p,ea}/c_{pa})A}$$

- **The total thermal resistance for matching evaporative cooling processes—flow rate matching & inlet parameter matching (inlet air at the saturation line)**

$$R_H=\frac{1}{k_s(c_{p,ea}/c_{pa})A}$$

For the matching process, heat transfer process is fully similar with mass transfer process, the whole process could be equivalent to a countercurrent heat transfer process with matching flow rate ratio.

Thermal resistance analysis for evaporative cooling processes

- When air-water flow rate ratio is unmatched, for evaporative cooling process,

$$R_H = \frac{1}{2}\left(\frac{1}{G_w c_{pw}} - \frac{1}{G_a c_{p,ea}}\right) \cdot \frac{e^{(m-1)k_s A/(G_a c_{pa})} + 1}{e^{(m-1)k_s A/(G_a c_{pa})} - 1} + \frac{1}{2} \cdot \frac{1}{G_a c_{p,ea}} \cdot \frac{c_{pa}}{r_0 a} \cdot \frac{(1 - m \cdot e^{(m-1)k_s A/(G_a c_{pa})})^2 (1 - e^{-2k_s A/(G_a c_{pa})})}{(1 - e^{(m-1)k_s A/(G_a c_{pa})})^2} \cdot \frac{(T_{a,in} - T_{sa,in})^2}{(T_{w,in} - T_{sa,in})^2}$$

where $m = \dfrac{G_a \cdot c_{p,ea}}{G_w \cdot c_{pw}}$

- The unmatching thermal resistance is,

$$R_{H,m} = \lim_{kA \to \infty} R_H$$

$$R_{H,m} = \frac{1}{2}\left(\frac{1}{G_w c_{pw}} - \frac{1}{G_a c_{p,ea}}\right) + \frac{1}{2} \cdot \frac{G_a c_{p,ea}}{(G_w c_{pw})^2} \cdot \frac{c_{pa}}{r_0 a} \cdot \frac{(T_{a,in} - T_{sa,in})^2}{(T_{w,in} - T_{sa,in})^2}$$

When m>1

$R_{H,fm}$—caused by unmatching flow rate ratio

$R_{H,pm}$—caused by unmatching inlet parameter

$$R_{H,m} = \frac{1}{2}\left(\frac{1}{G_a c_{pea}} - \frac{1}{G_w c_{pw}}\right) + \frac{1}{2}\frac{1}{G_a c_{pea}}\frac{c_{pa}}{r_0 a}\frac{(T_{a,in} - T_{sa,in})^2}{(T_{w,in} - T_{sa,in})^2}$$

When m<1

$$R_{H,m} = R_{H,fm} + R_{H,pm}$$

$R_{H,fm}$, depends only on flow rate ratio

$R_{H,pm}$, depends mainly on inlet parameter of air and water, influenced by air-water flow rate ratio

Thermal resistance analysis for evaporative cooling processes

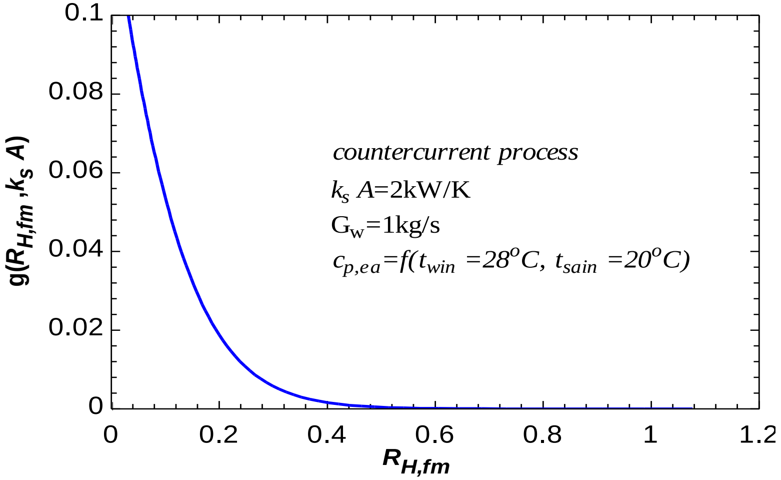
When air-water flow rate ratio is unmatched

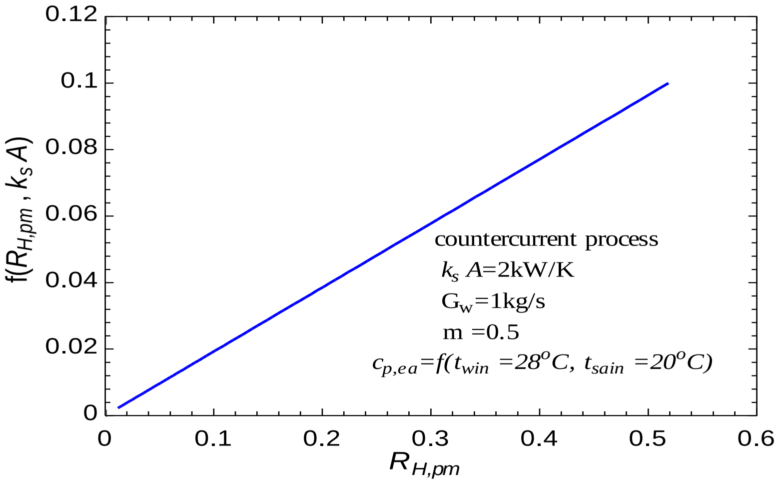
- The left thermal resistance—thermal resistance caused by finite heat transfer area:

$$R_{H,f} = R_H - R_{H,m}$$

$$R_{H,f} = R_{H,fm}\frac{2e^{-2k_sA(c_{p,ea}/c_{pa})R_{H,fm}}}{1-e^{-2k_sA(c_{p,ea}/c_{pa})R_{H,fm}}} + R_{H,pm}\left(\frac{(1-me^{-2k_sA(c_{p,ea}/c_{pa})R_{H,fm}})^2(1-e^{-2k_sA/(G_ac_{pa})})}{(1-e^{-2k_sA(c_{p,ea}/c_{pa})R_{H,fm}})^2}-1\right)$$ When m<1

$$R_{H,f} = g(R_{H,fm}, k_sA) + f(R_{H,pm}, k_sA)$$





- The higher the unmatched thermal resistance caused by flow rate ratio($R_{H,fm}$), the lower the corresponding thermal resistance caused by finite heat transfer area($g(R_{H,fm}, K_sA)$).
- The higher the unmatched thermal resistance caused by inlet parameter of air and water($R_{H,pm}$), the higher the corresponding thermal resistance caused by finite heat transfer area($f(R_{H,pm}, K_sA)$).

Thermal resistance analysis for evaporative cooling processes

When air-water flow rate ratio is unmatched

- The left thermal resistance—thermal resistance caused by finite heat transfer area:

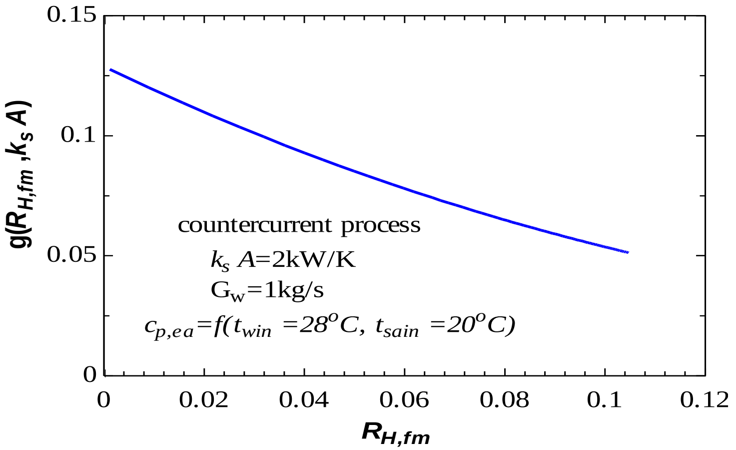
$$R_{H,f} = R_H - R_{H,m}$$

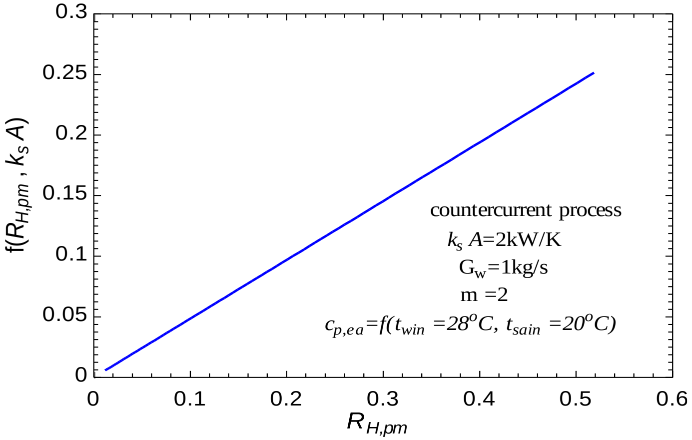
$$R_{H,f} = R_{H,fm} \cdot \frac{2e^{-2k_sA(c_{p,ea}/c_{pa})R_{H,fm}}}{1-e^{-2k_sA(c_{p,ea}/c_{pa})R_{H,fm}}} + R_{H,pm} \cdot \left(\frac{[1-(1/m)e^{-2k_sA(c_{p,ea}/c_{pa})R_{H,fm}}]^2(1-e^{-2k_sA/(G_ac_{pa})})}{(1-e^{-2k_sA(c_{p,ea}/c_{pa})R_{H,fm}})^2} - 1\right)$$

When m>1

$$g(R_{H,fm}, k_sA) = R_{H,fm} \cdot \frac{2e^{-2k_sA(c_{p,ea}/c_{pa})R_{H,fm}}}{1-e^{-2k_sA(c_{p,ea}/c_{pa})R_{H,fm}}}$$

$$f(R_{H,pm}, k_sA) = R_{H,pm} \cdot \left(\frac{[1-(1/m)e^{-2k_sA(c_{p,ea}/c_{pa})R_{H,fm}}]^2(1-e^{-2k_sA/(G_ac_{pa})})}{(1-e^{-2k_sA(c_{p,ea}/c_{pa})R_{H,fm}})^2} - 1\right)$$





- The higher the unmatched thermal resistance caused by flow rate ratio($R_{H,fm}$), the lower the corresponding thermal resistance caused by finite heat transfer area(*$g(R_{H,fm}, K_sA)$*).
- The higher the unmatched thermal resistance caused by inlet parameter of air and water($R_{H,pm}$), the higher the corresponding thermal resistance caused by finite heat transfer area(*$f(R_{H,pm}, K_sA)$*).

Using T-Q chart and ω-W chart for internal losses analysis

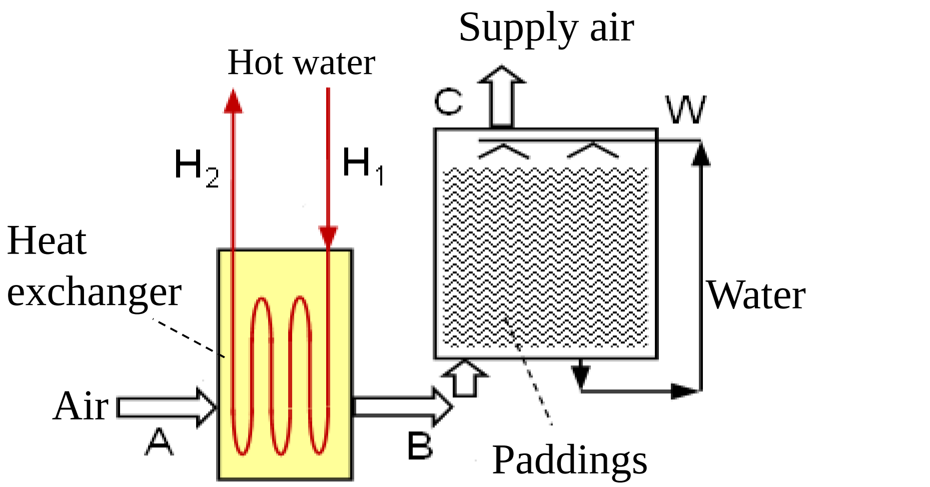
- It is very interesting that, the total equivalent heat and mass transfer resistance could be deducted to be the sum of inlet parameter unmatching thermal resistance, flow pattern unmatching thermal resistance, flow rate unmatching thermal resistance, thermal resistance caused by limited heat transfer area.
- That means the thermal resistance caused by different irreversible factors could be added to together.

$$R_{total}=R_{p,m}+R_{fp,m}+R_{fr,m}+R_A$$

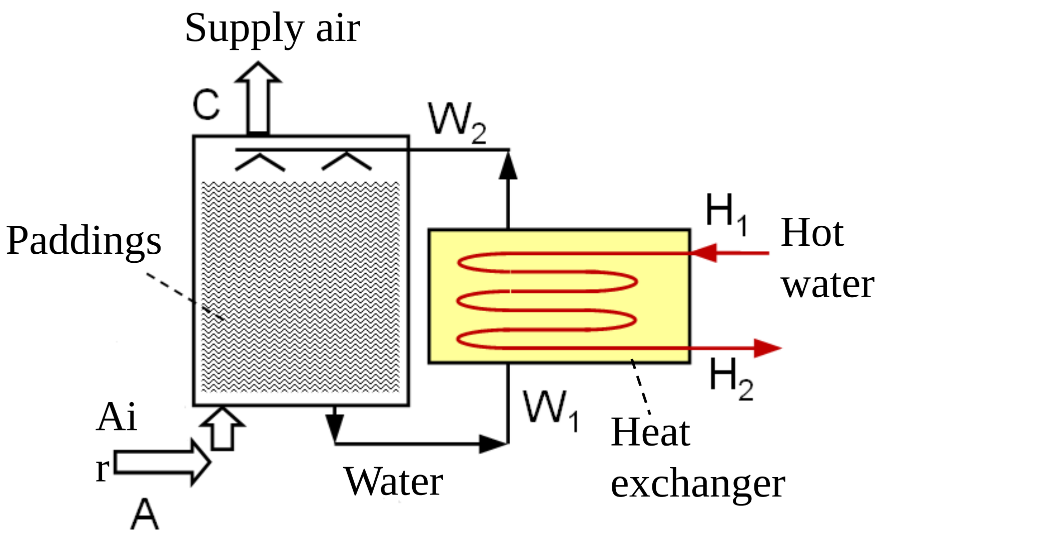
- For real processes, with temperature difference for heat transfer and humidity ratio difference for mass transfer, and considering the total heat and mass transfer area cost, the process structure could be a little different from ideal and matching process, as to get a minimum total thermal resistance.

One Case—Application of the thermal resistance analysis method

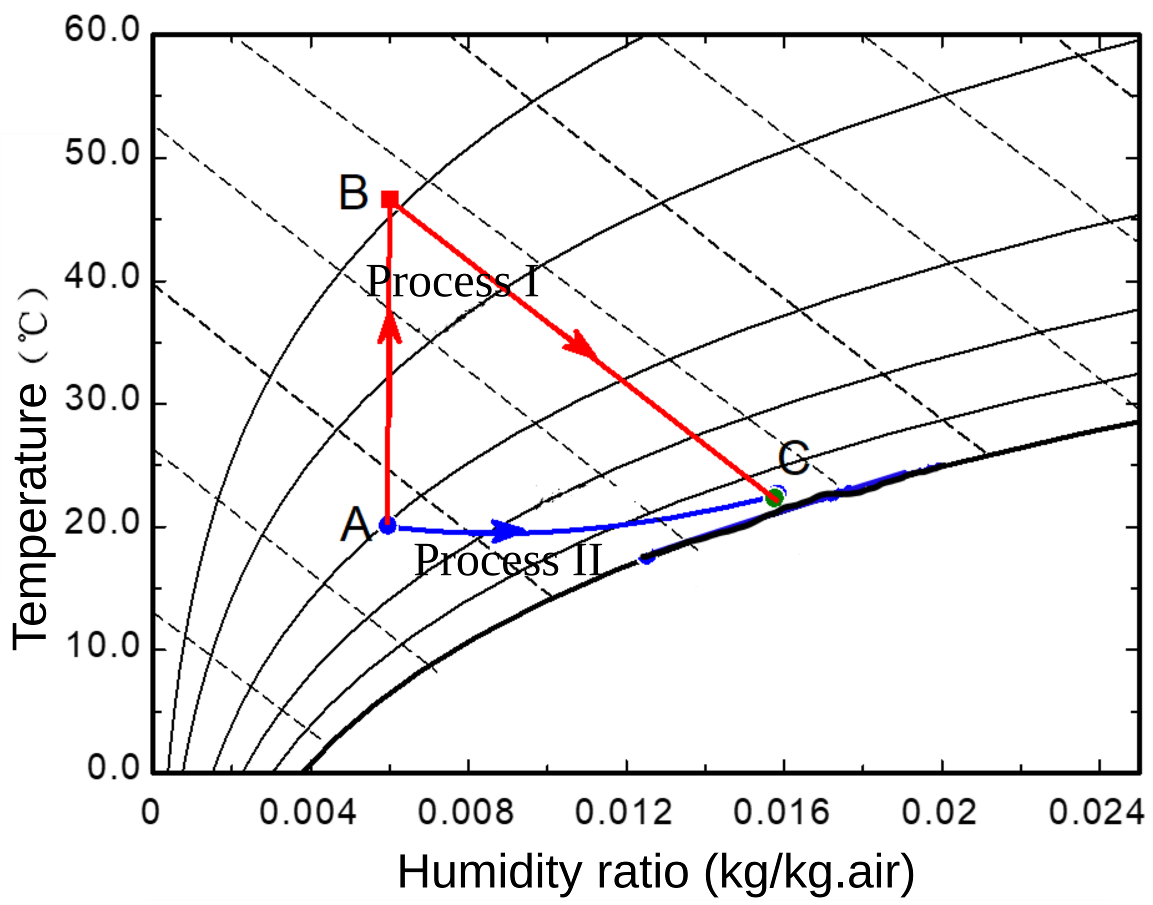
- Comparing two different humidification processes, which one is better?



Process I: Air humification by heating inlet air

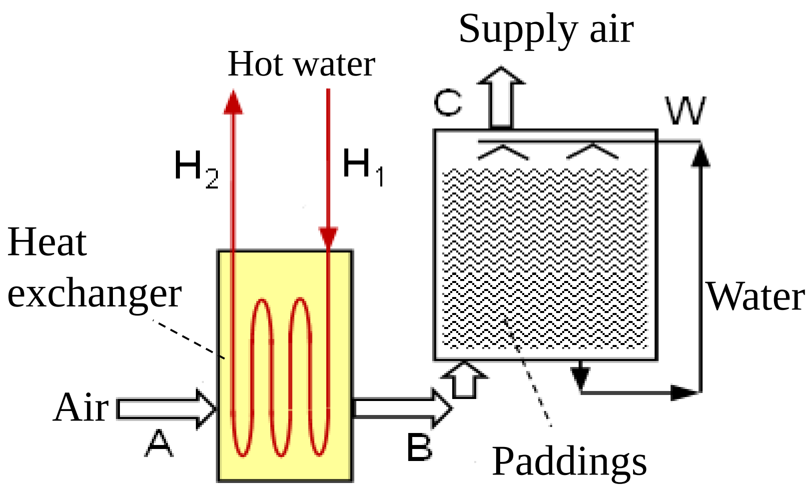


Process II: Air humification by heating cycled water

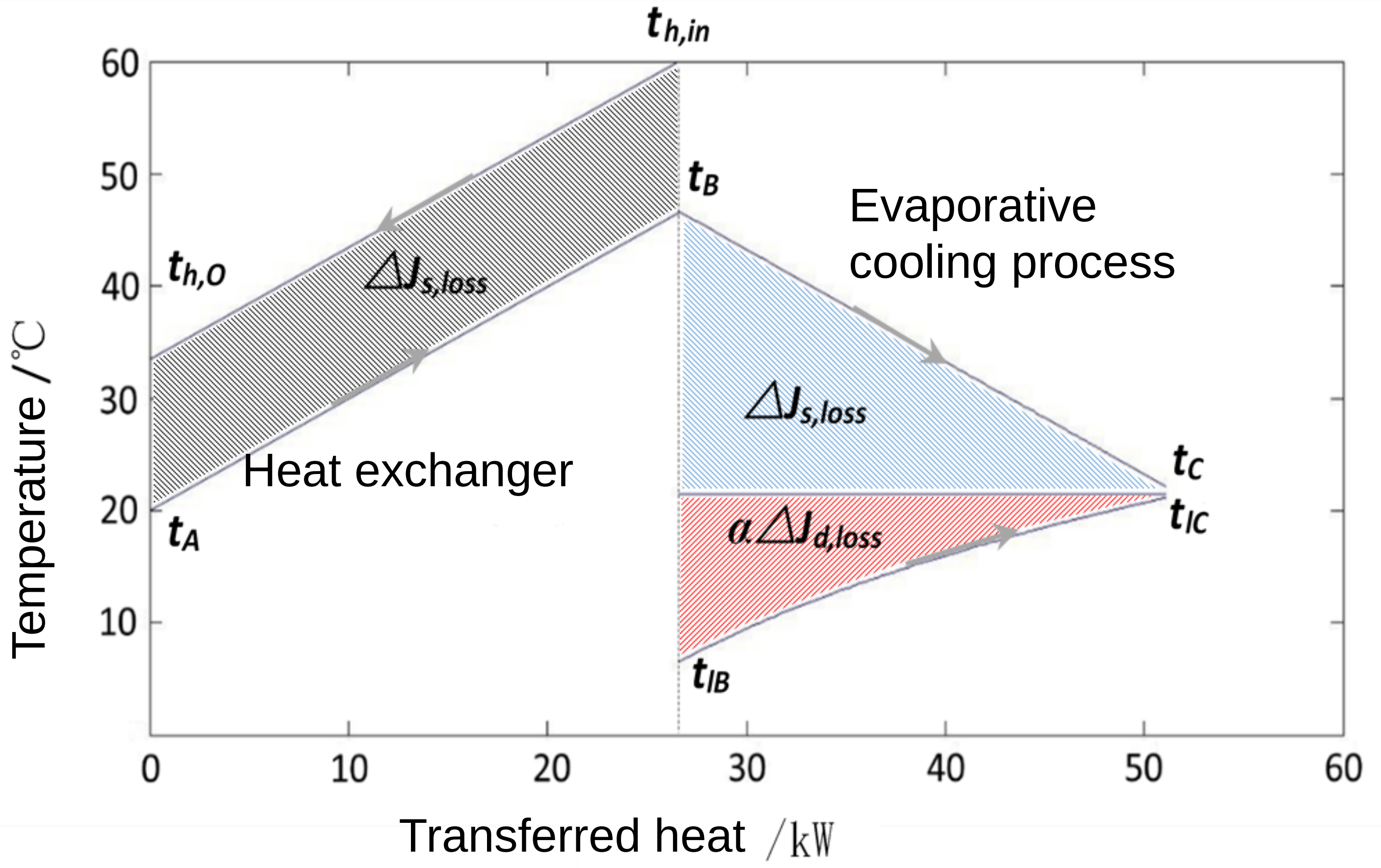


One Case—Application of the thermal resistance analysis method

- Heat transfer and mass transfer processes shown on T-Q chart, process I

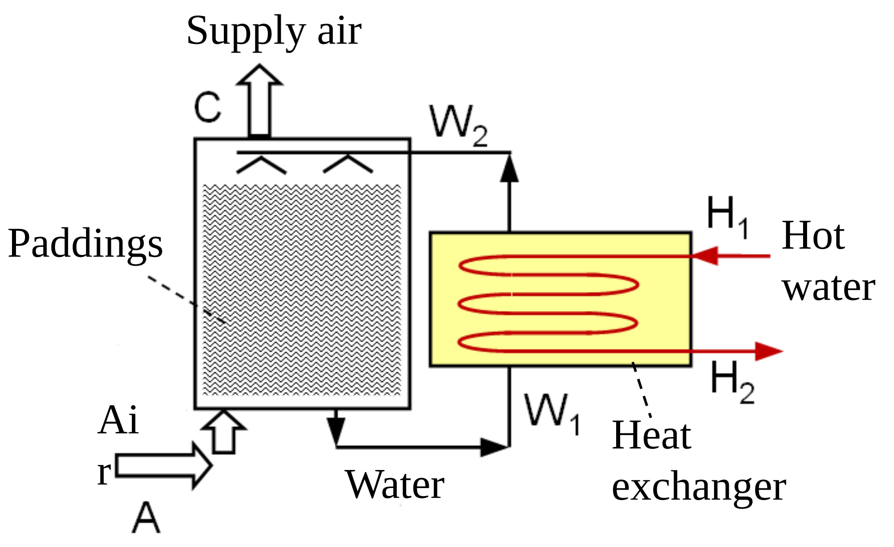


Process I: Air humification by heating inlet air

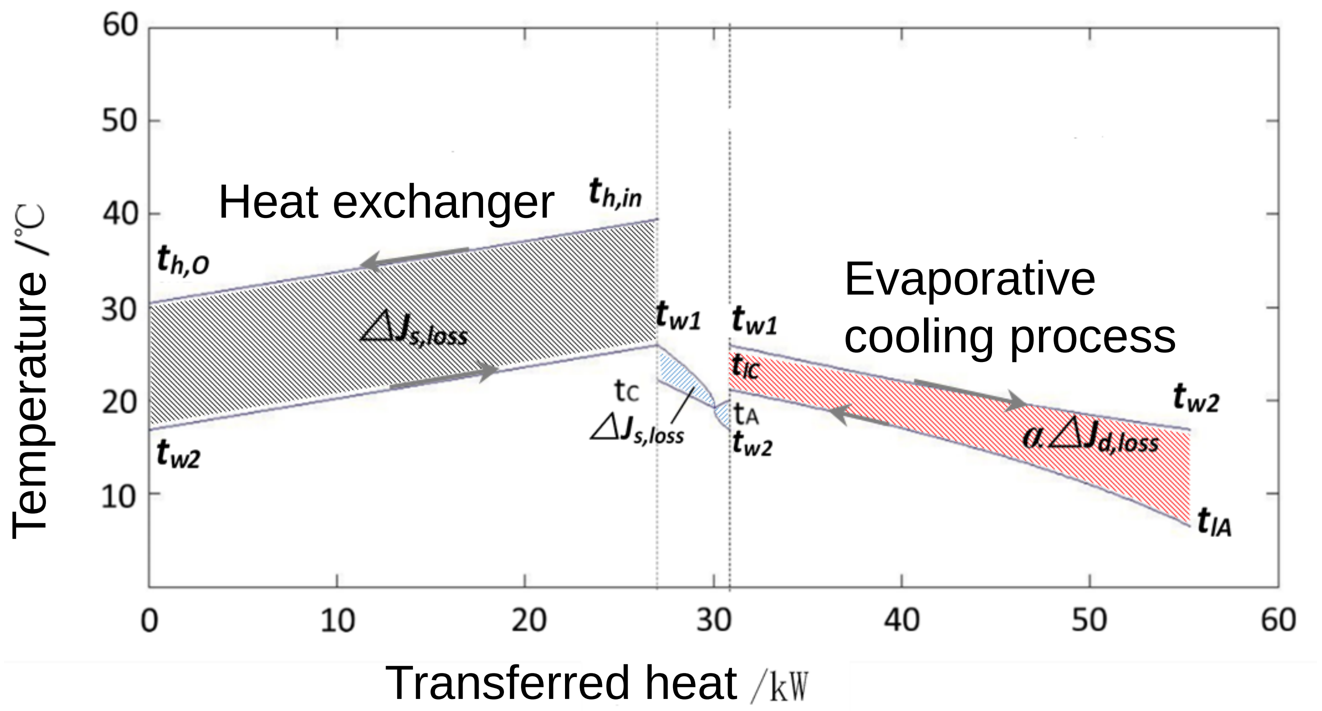


One Case—Application of the thermal resistance analysis method

- Heat transfer and mass transfer processes shown on T-Q chart, process II



Process II: Air humification by heating cycled water



One Case—Application of the thermal resistance analysis method

	Hot water heat exchanger				Evaporative cooling tower				Hot water inlet temperature
	KA (kW/ºC)	R_H	$R_{H,m}$	$R_{H,f}$	KA (kW/ºC)	R_H	$R_{H,m}$	$R_{H,f}$	(ºC)
Process I	2.0	0.5	0	0.5	3.6	0.76	0.72	0.04	60
Process II	2.0	0.5	0	0.5	2	0.24	0.03	0.21	39.5

Note: when calculating the thermal resistance of these two processes, Q is used as the latent heat of humification, as the main purpose is for air humification, which is a little different with the front thermal resistance definition.

- Process II (heating water for air humification) is better than process I (heating air for air humidification) : the demanded hot water inlet temperature of process II is 20.5 ℃ lower than that of process I, and KA of evaporative cooling tower of process II is only 55% of that of process I.
- The main reason, the unmatching thermal resistance caused by inlet parameter of evaporative cooling process of process I is much higher than that of process II, as the iso-enthalpy humification processes.
- Using thermal resistance analysis method, the processes with different structure could be compared.

Conclusions

- As to see the heat transfer and mass transfer processes clearly, T-Q chart and ω-W Chart could be used to describe the transfer processes, as well as to show the transfer losses.
- For merely heat transfer process, the heat transfer losses is caused mainly by unmatching flow rate, unmatching flow type, and limit heat transfer area, which could be identified by equivalent thermal resistance defined by entransy loss shown in T-Q chart.
- For evaporative cooling process, the heat transfer and mass transfer losses is caused by unmatching inlet parameter, unmatching flow rate, unmatching flow type and limit heat transfer area, which could be identified by total equivalent thermal resistance combined entransy loss shown in T-Q chart and ω-W Chart together.
- From DEC to IEC, the key point is to meet inlet parameter matching, that is to make the inlet air of evaporative cooling process near the saturation line, thus to make the limit outlet air/water temperature to near inlet dew point temperature.
- Using thermal resistance analysis method, the processes with different structure could be compared.

Thank you very much for your attention.

xiexiaoyun@tsinghua.edu.cn