What is evaporative cooling:
its characteristics, performance, main technology: IEC water chiller and IEC air cooler

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for HVAC professionals

Outline

- Evaporative cooling: Internal heat and mass transfer processes
- Performance analysis of Indirect Evaporative Cooling(IEC) Technologies
  - Cooling performance and water consumption performance
  - Different IEC systems comparison
  - Optimization of different IEC processes
- Application of IEC technologies
  - Existed projects of IEC technologies
  - Feasibility analysis of IEC water chillers in typical cities of China

Background

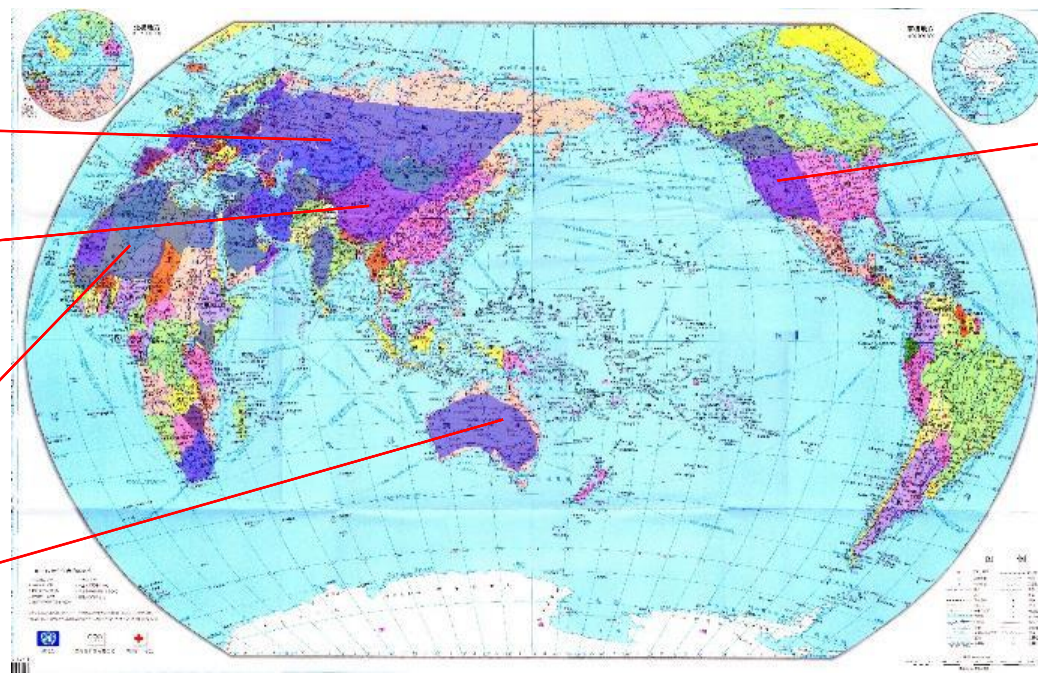
- Although over 85% of cooling around the world is achieved by mechanical refrigeration, more than 40% buildings of the regions where cooling is needed can be cooled by evaporative cooling instead mechanic, due to the dry climates.

Countries in Europe: North France, Germany, Holland, most part in Russia

Asia: North west of China, Mongolia, Saudi Arabia, Kazakhstan, middle of india

North of Africa

Australia



West of the U.S., South west of Canada

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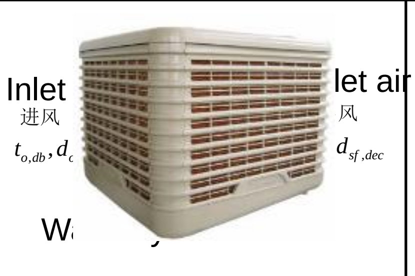
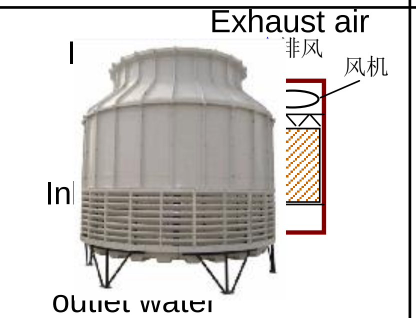
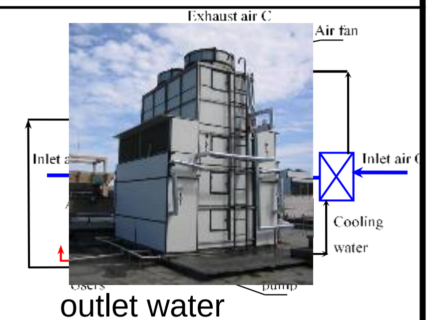
Evaporative cooling technologies

- Evaporative cooling is to make water directly or indirectly contact with air of low relative humidity, thus water evaporated to realize cooling effect.

	Direct Evaporative Cooling (DEC) **Limit is inlet wet bulb temperature**	**Indirect Evaporative Cooling (IEC)** **Limit is inlet dew point temperature**
To produce cooling air		
To produce cooling water		

- Using IEC technology, the output temperature of water or air can be 6-10K lower than using DEC technology, and 3-5K lower than the inlet wet bulb temperature, reaching around 14-18℃ at ambient temperature of 35℃-38℃ and relative humidity of 20%-25%.
- Using IEC technology, electricity consumption can be reduced by 40%~70% compared with common mechanical chiller system, and no CFCs used.

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1. **Evaporative cooling:** Internal heat and mass transfer processes

Basic process of Evaporative cooling

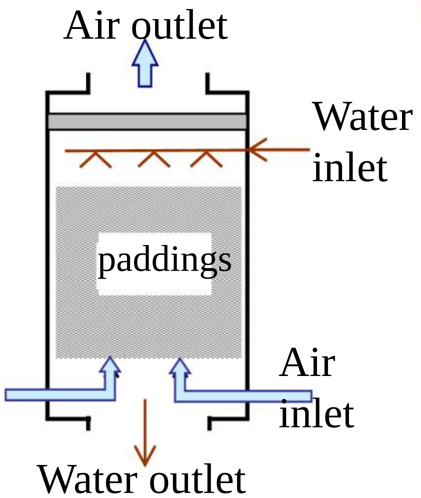
- For countercurrent water-air direct contact heat and mass transfer processes,

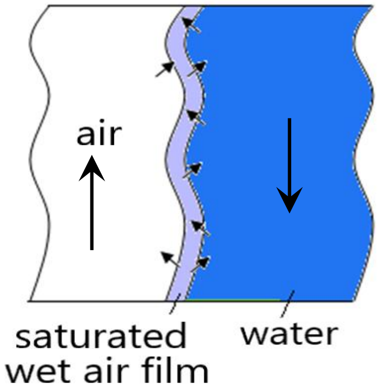
$$G_a c_{pa} dt_a = -K_s dA\,(t_w - t_a)$$

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

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

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





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) .

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.**

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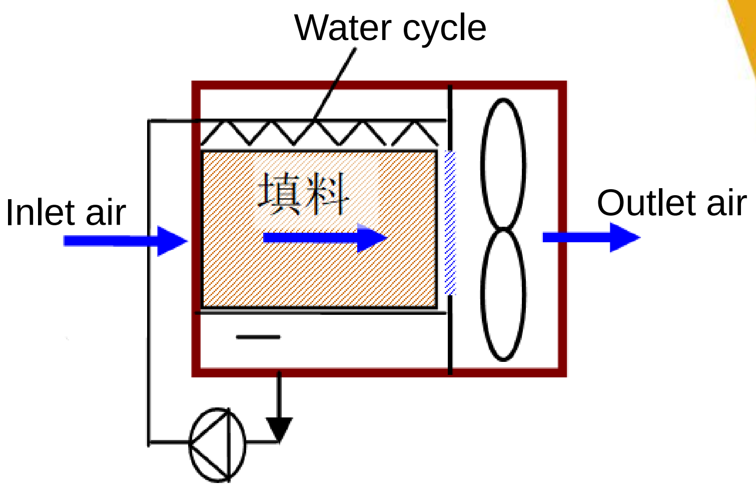
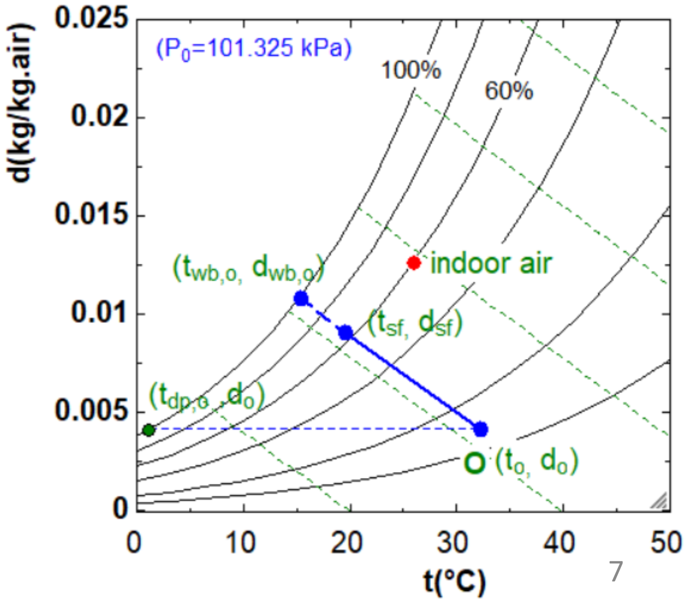
Basic process of Evaporative cooling

- For direct evaporative air cooling process, inlet air and the saturated air of water are at the same isoenthalpy line:
  - Air is cooled along the isoenthalpy line, with humidity ratio is increased;
  - Water is remaining at the intersection point of the air isoenthalpy line and water saturation line.
  - **Outlet limit air temperature is inlet wet bulb temperature, why it could not low to inlet dewpoint temperature?**





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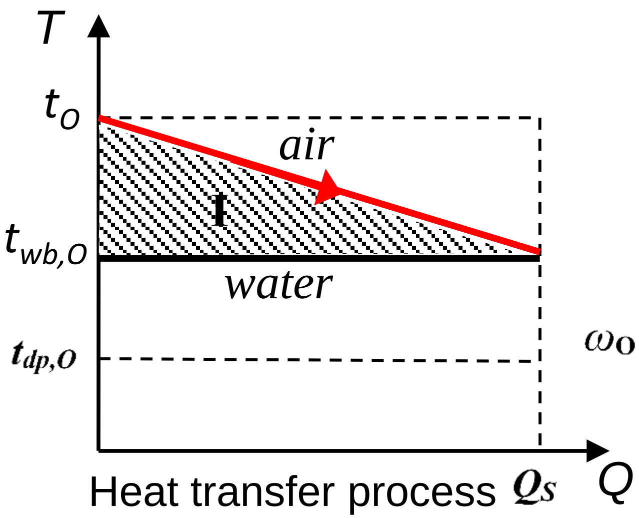
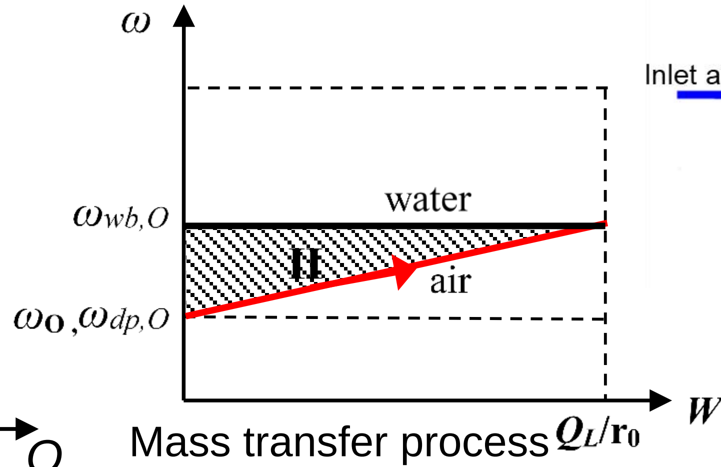
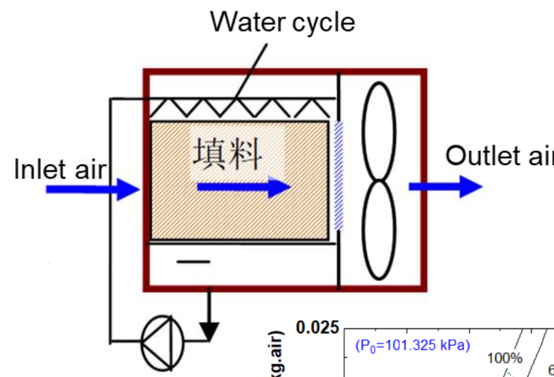
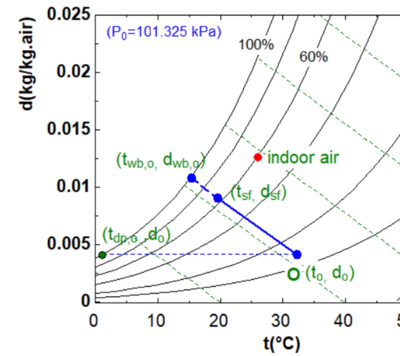
Basic process of Evaporative cooling

- For heat and mass transfer processes





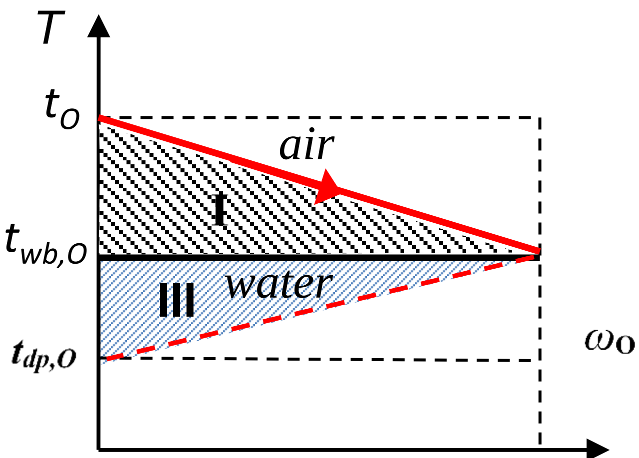




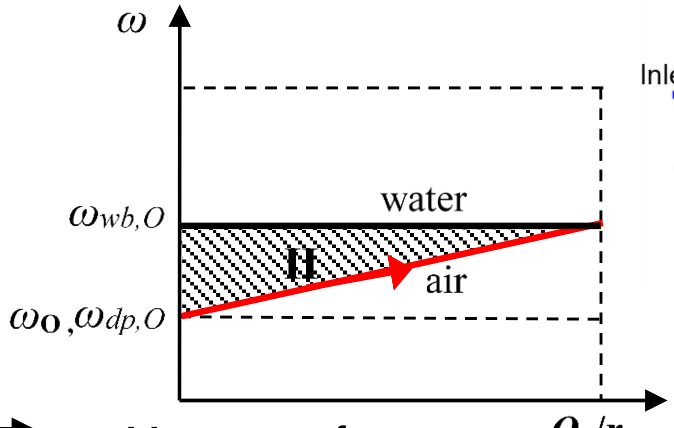
- **Air transfer heat to water, while water transfer moisture to air, the transfer direction for heat and moisture is opposite.**
- Area I is heat grade loss caused by heat transfer, also called heat transfer entransy dissipation;
- Area II is humidity grade loss caused by mass transfer, also called mass transfer entransy dissipation;
- **For air-water heat and mass transfer processes with opposite direction, the grade 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.**

Basic process of Evaporative cooling

- For heat and mass transfer processes

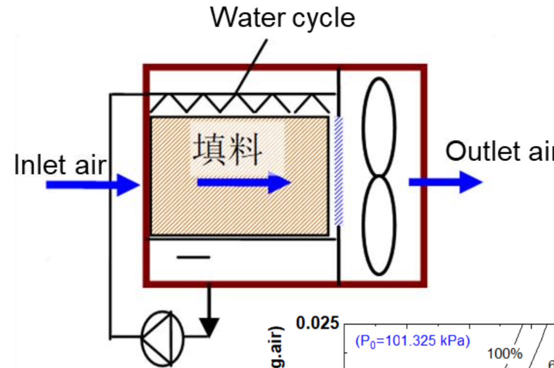


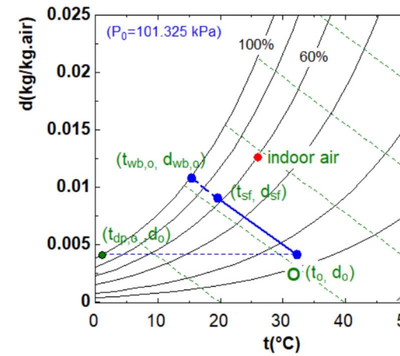
Heat transfer process Q_S



Mass transfer process Q_L/r_0

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

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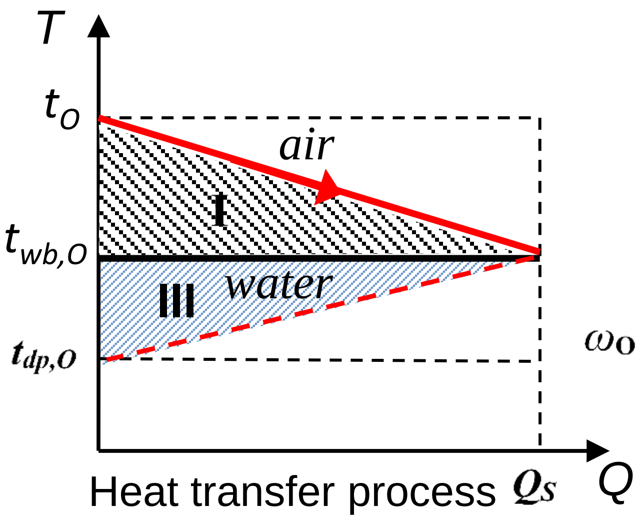
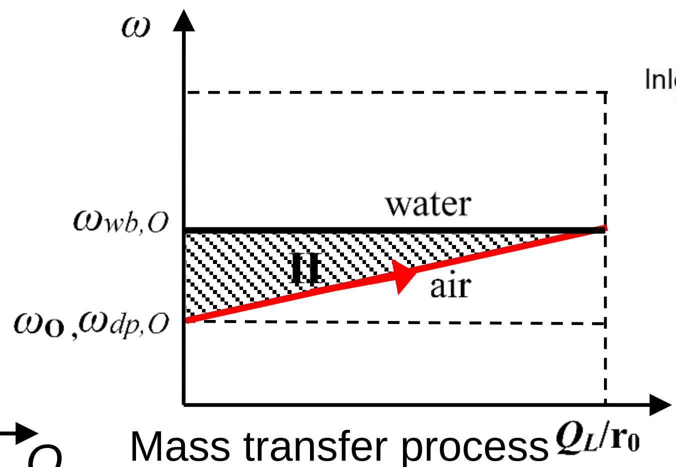
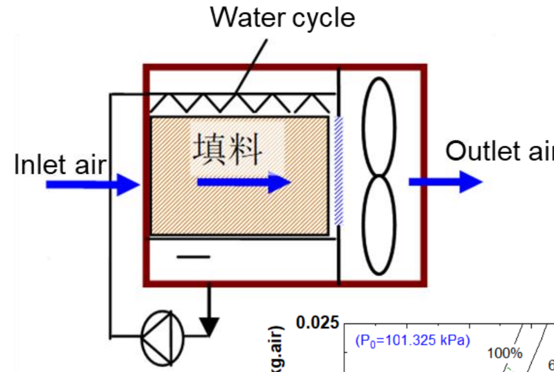
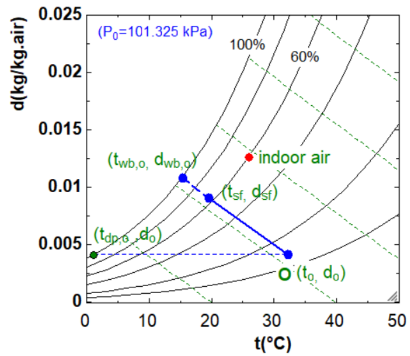
Basic process of Evaporative cooling

- 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.**

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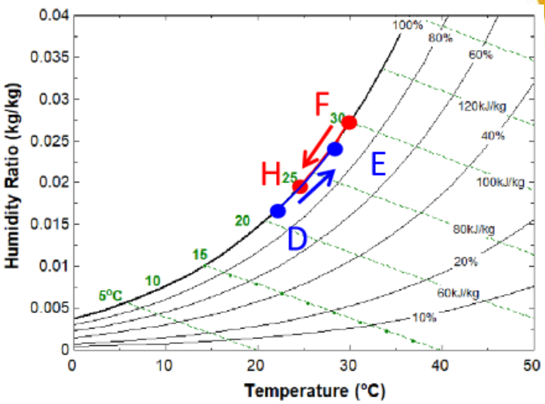
Matching Evaporative cooling progress

- 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



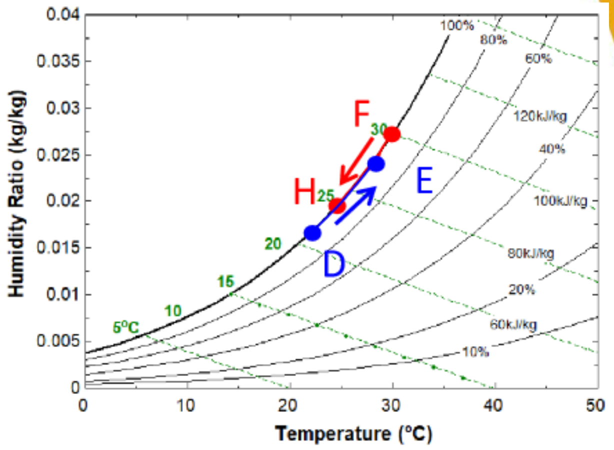
- Matching flow rate ratio of air and water is designed
  - Equivalent specific heat of air is defined, as $c_{p,ea}$
  - Matching flow rate ratio, $\boxed{m = 1}$

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

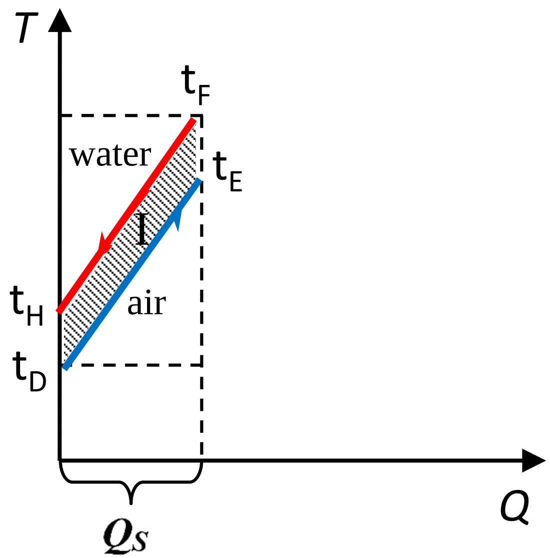
$$c_{p,ea} = \frac{dh_{ea}}{dt_{ea}} = \frac{h_E - h_D}{T_E - T_D} = c_{pa} + r_0 \cdot \frac{\Delta\omega}{\Delta T}$$

Matching Evaporative cooling progress

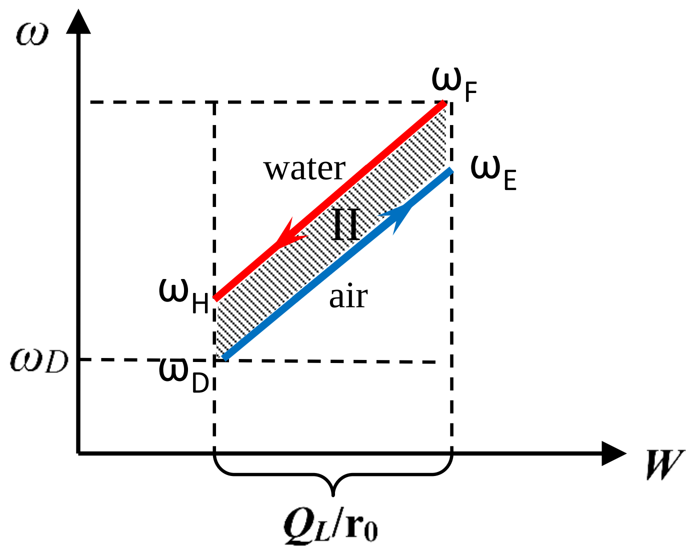
- For direct evaporative cooling process, if the inlet air is at the saturation line:
  - Air is heated and humidified, from D to E
  - Water is cooled, from F to H



- 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,

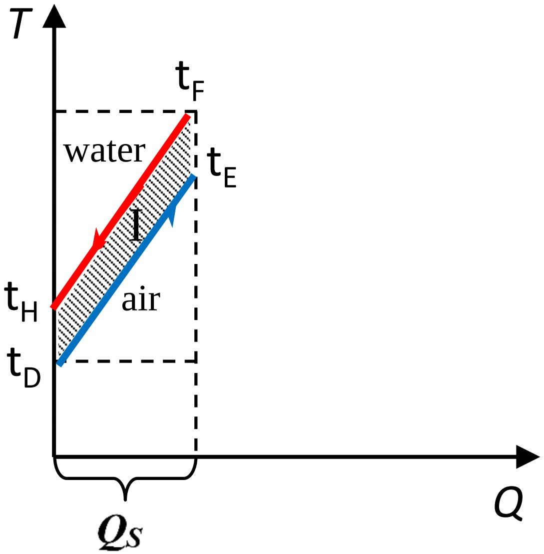


Heat transfer process

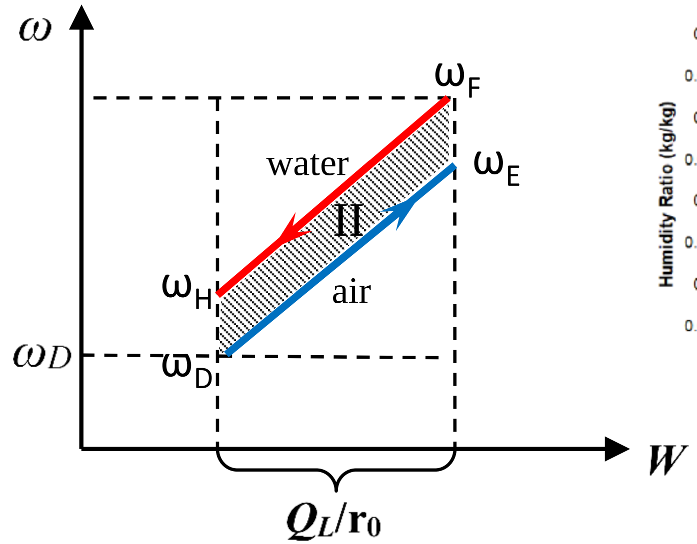


Mass transfer process

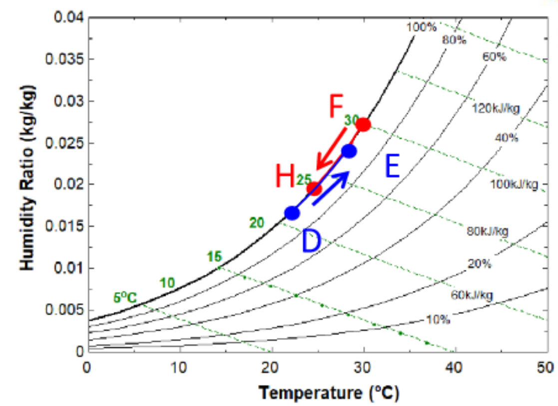
Matching Evaporative cooling progress



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 transfer 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.**

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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, $m = \frac{G_a \cdot c_{p,ea}}{G_w \cdot c_{pw}} = 1$

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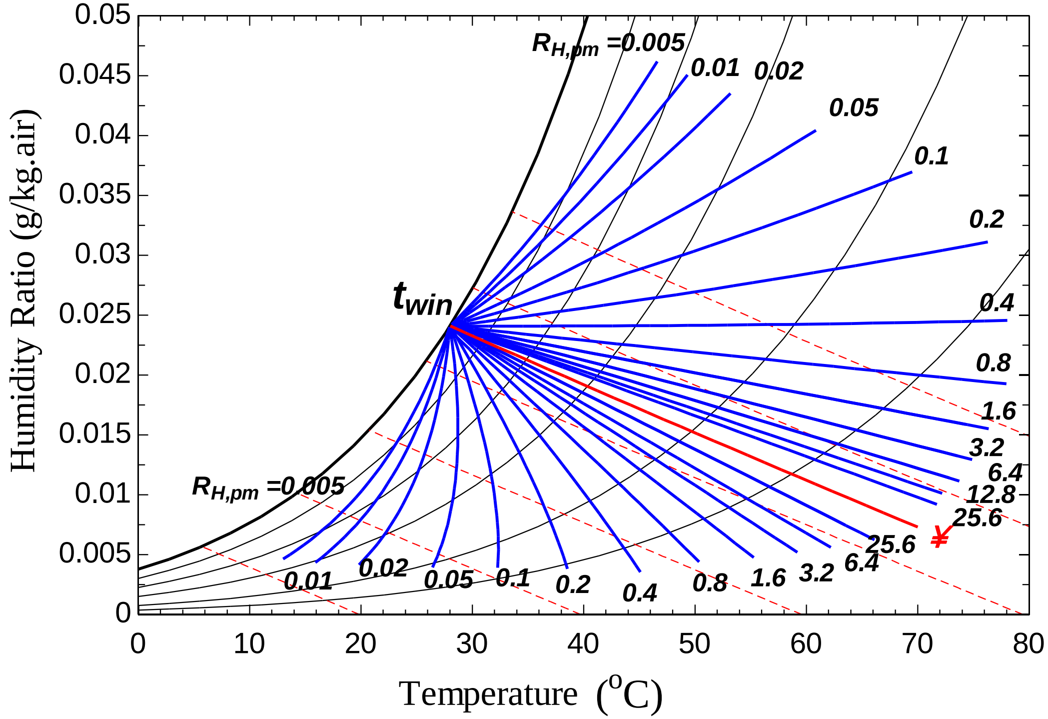
Matching Evaporative cooling progress

- An equivalent unmatching thermal resistance is defined used the entransy dissipation. The iso-parameter unmatching thermal resistance lines could be drawn. The nearer the inlet air to the saturation line, the lower the parameter unmatching thermal resistance.



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

Where $\Delta J_{d,loss}$ *is the entransy dissipation of mass transfer process,* $\Delta J_{s,loss}$ *is the entransy dissipation of heat transfer process, α is a factor, α=r*$_0$*/a, if the part of the saturation line could be assumed linear, α could be a constant.*

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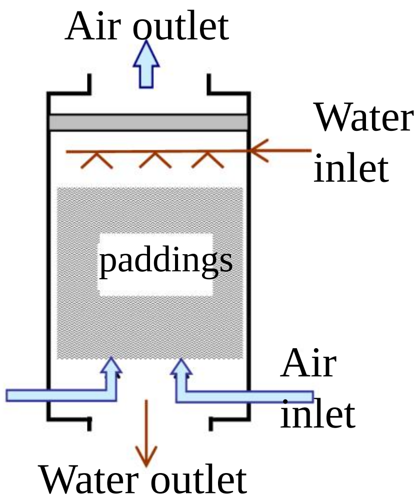
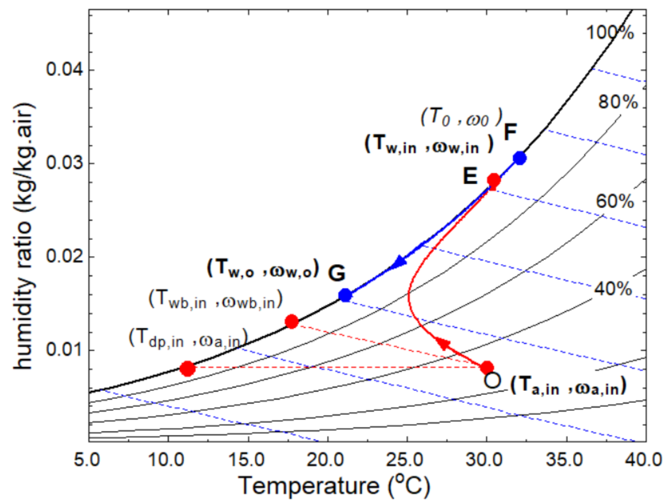
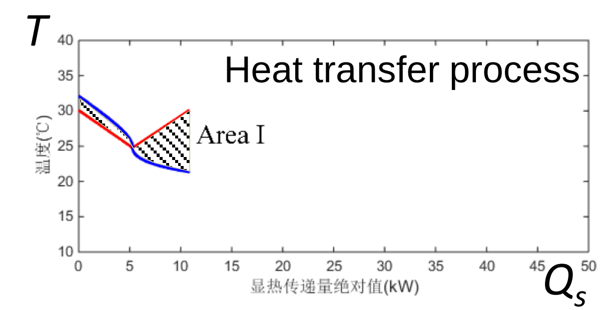
Common evaporative cooling progress

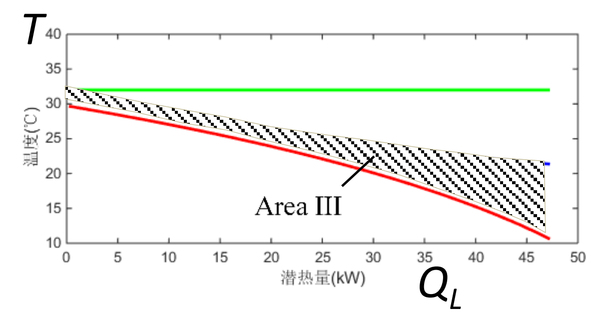
- Common countercurrent cooling tower processes

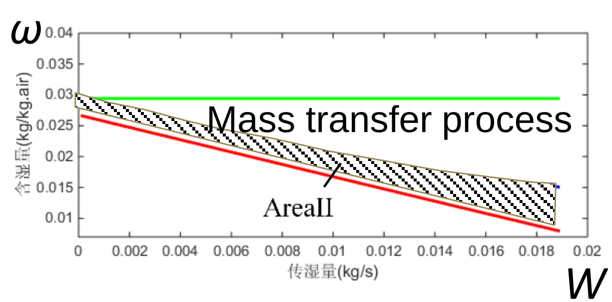




- Flow rate between air and water could be matched;
- While inlet air is far from saturation line, inlet parameter unmatching.



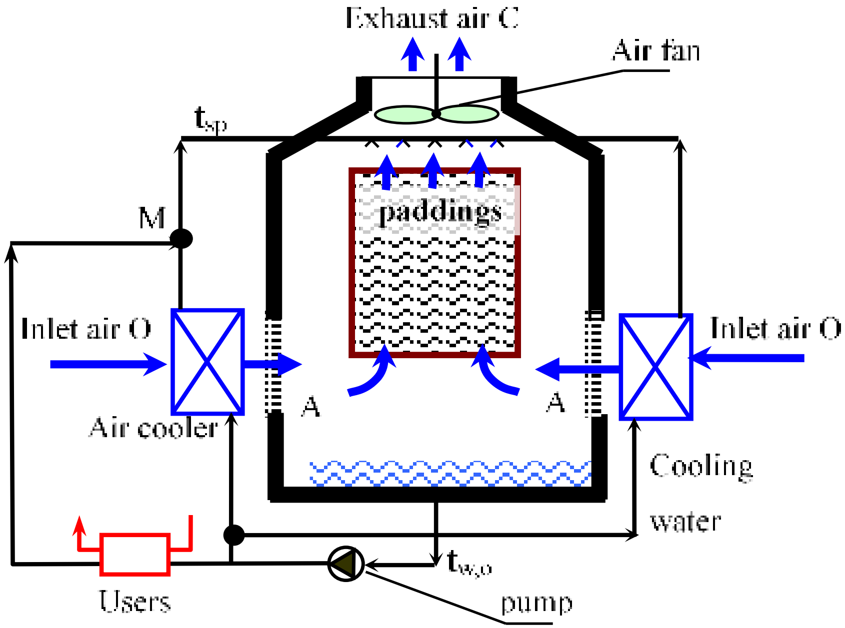


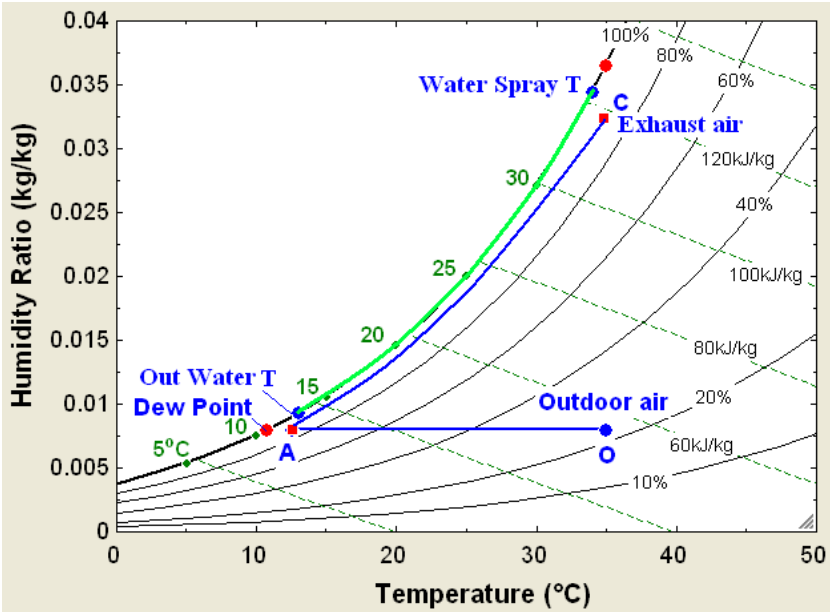


Area III, equivalent entransy dissipation of mass transfer (Area II) in T-Q chart

Near reversible evaporative cooling progress

- 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 counter current padding tower;
  - **Flow rate matching design** for each of the heat transfer or heat and mass transfer process.

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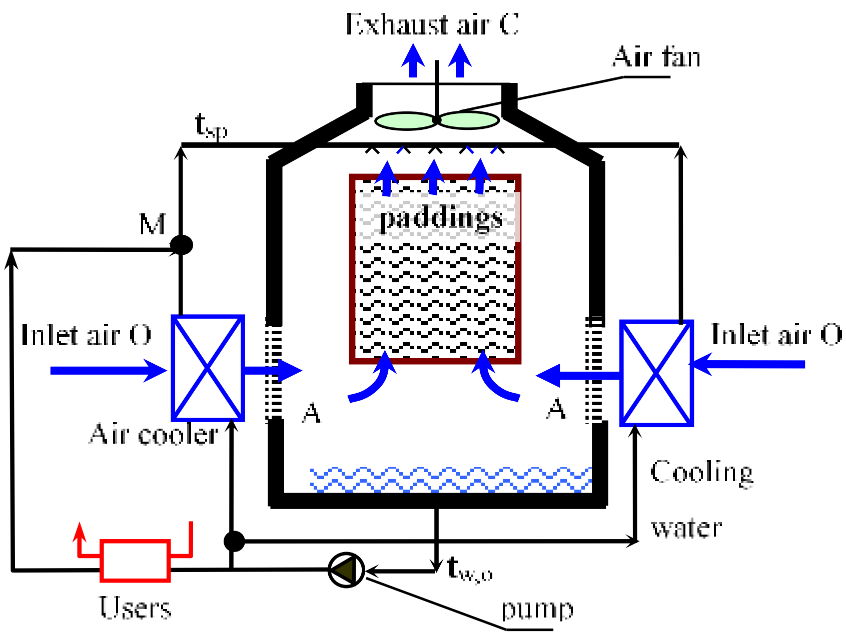
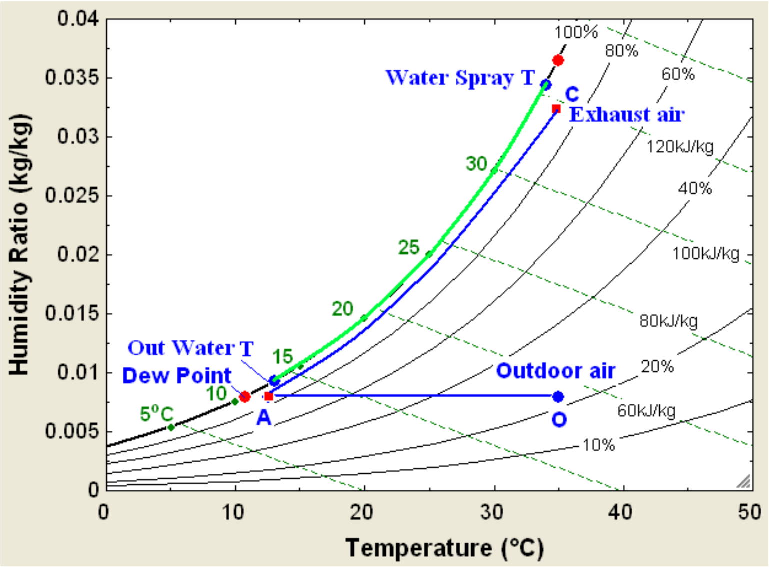
Indirect Evaporative water chiller process





- Matching flow rate:

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

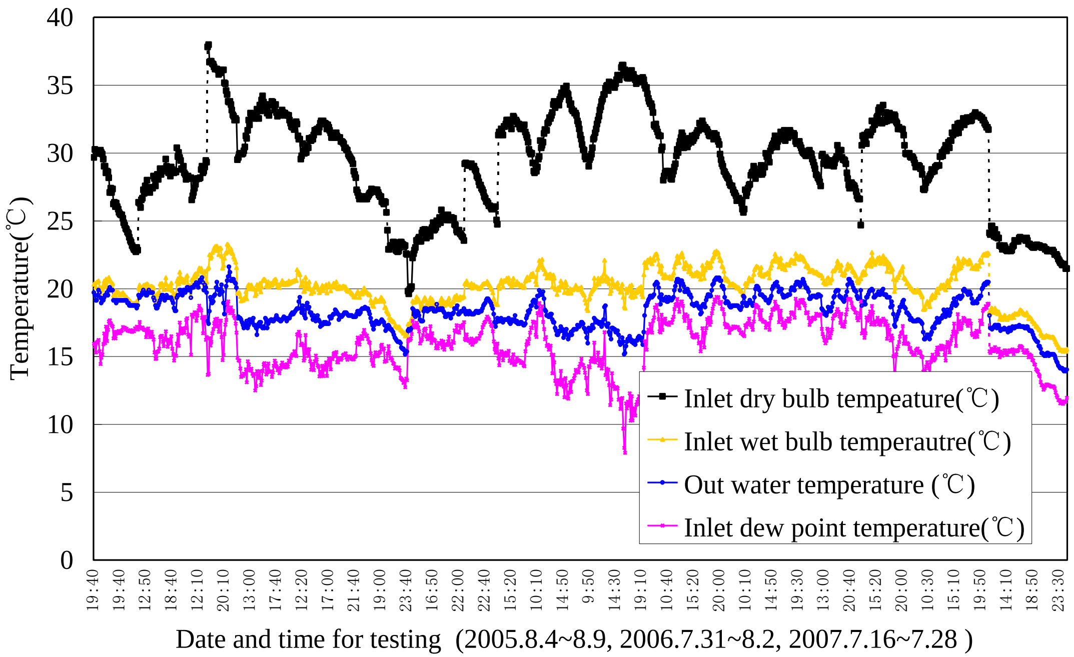
For cooling tower, $(G_{w1}+G_w)c_{pw} = G_a c_{pea}$

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 vey low temperature difference caused by non-linear of the saturation line.

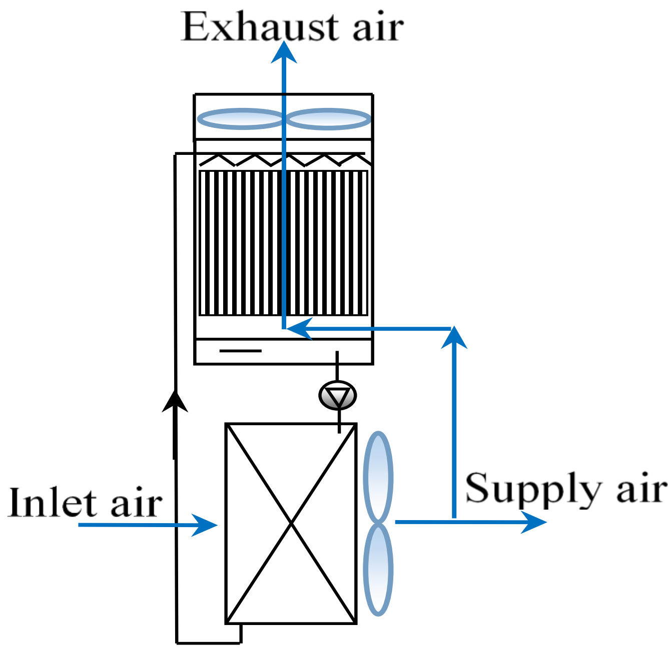
Indirect Evaporative water chiller process

- The real developed indirect evaporative chiller, the tested outlet water temperature is lower than inlet wet bulb and higher than inlet dew point temperature, and more or less at the middle value of inlet wet bulb and dew point.

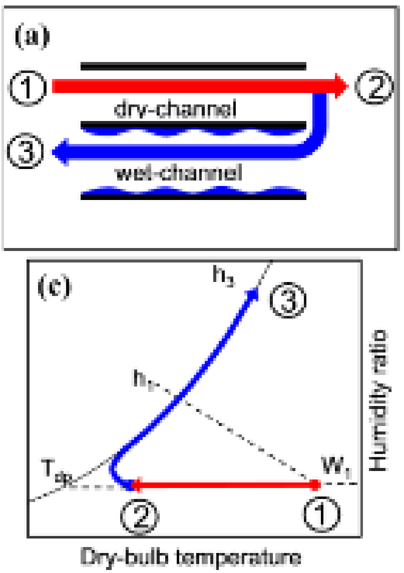


Near reversible evaporative cooling progress

- 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.

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Kinds of existed indirect evaporative cooling processes

- 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.
- The total equivalent heat and mass transfer resistance could be the sum of parameter unmatching thermal resistance, flow pattern unmatching thermal resistance, flow rate unmatching thermal resistance, thermal resistance caused by limited heat transfer area.

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

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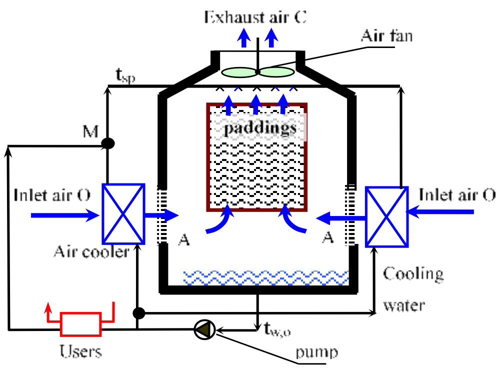
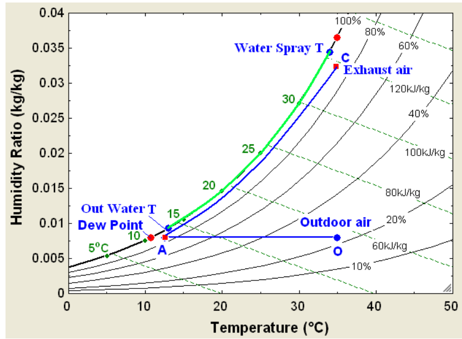
Kinds of existed indirect evaporative cooling processes

- Indirect evaporative chillers





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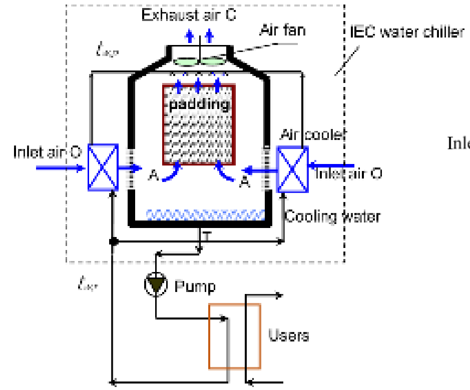

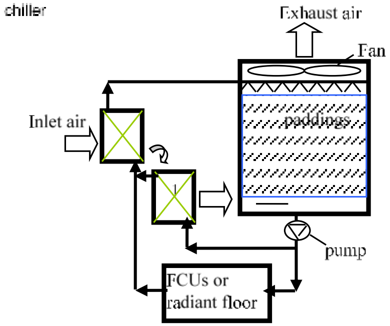

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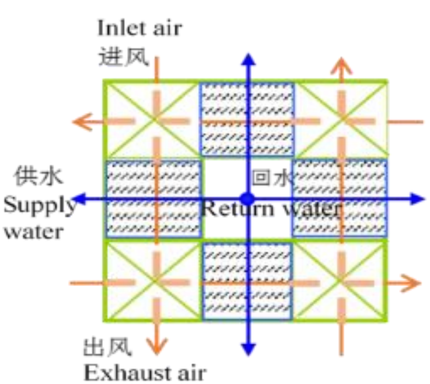
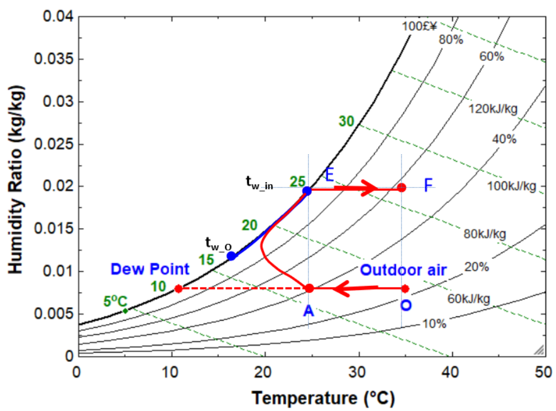
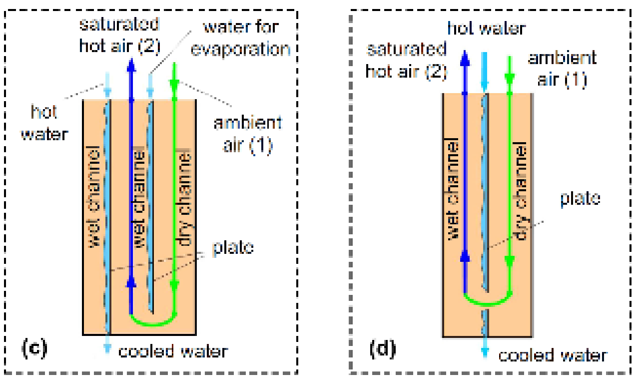




Yi Jiang, Xiaoyun Xie, Comparison of two indirect cooling processes to produce cold water, Proceedings of 25th IIR International Congress of Refrigeration, Montreal, Canada, August 24-30, 2019, p4153-4160.

- IEC water chillers using IEC air cooler module to pre-cool inlet air



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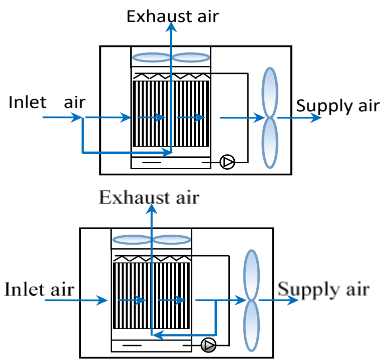
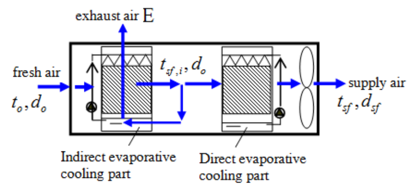
Kinds of existed indirect evaporative cooling processes

- Indirect evaporative air coolers

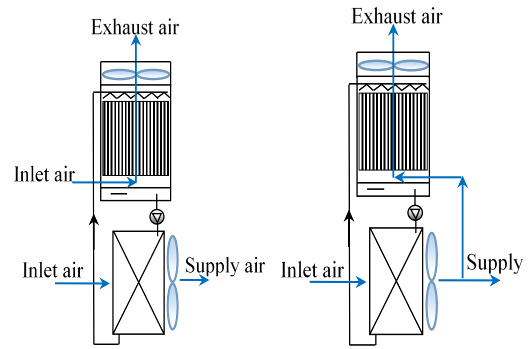


Internal IEC air coolers

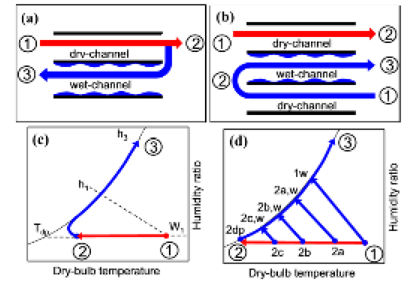


Multi-stage processes

Xiaoyun Xie, Yi Jiang, Comparison of Two Kinds of Indirect Evaporative Cooling System: To Produce Cold Water and To Produce Cooling Air, Procedia Engineering, 2015, 121: 881-890

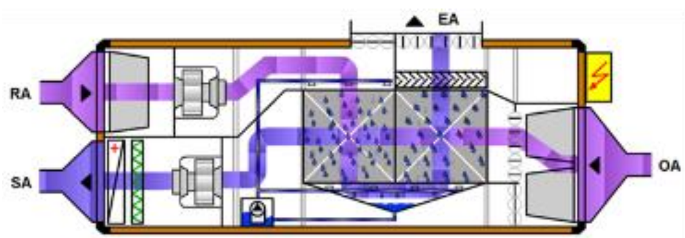


External IEC coolers

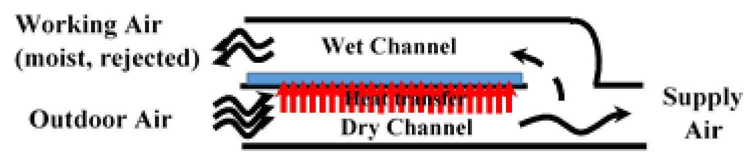


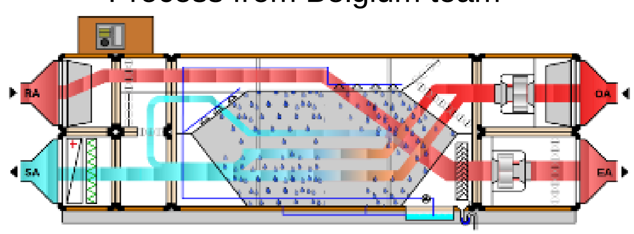
M-Cycle IEC air coolers

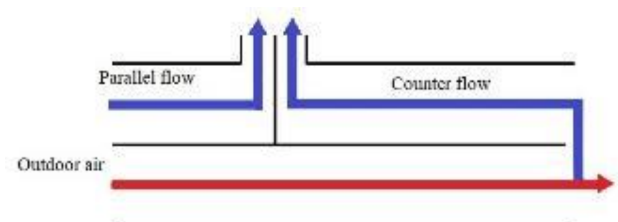
Muhammad H. Mahmood, et al . Overview of the Maisotsenko cycle – A way towards dewpoint evaporative cooling. 2016. Renewable and Sustainable Energy Reviews, 66(2016): 537~555



Process from Belgium team







Process from Belgium team

Internal IEC air coolers, using room exhaust air, part of the supply air as the supply air

Djallel Abada, Chadi Maalouf, Tala Moussa, Amel F. Boudjabi, Guillaume Polidori, Djamila Rouag Saffidine, Oualid Sotehi, Zoheir Derghout and Etienne Wurtz (2019). Design of a dew point evaporative cooler for buildings in Mediterranean climate, Conférence CLIMA 2019, Bucarest mai, 2019.

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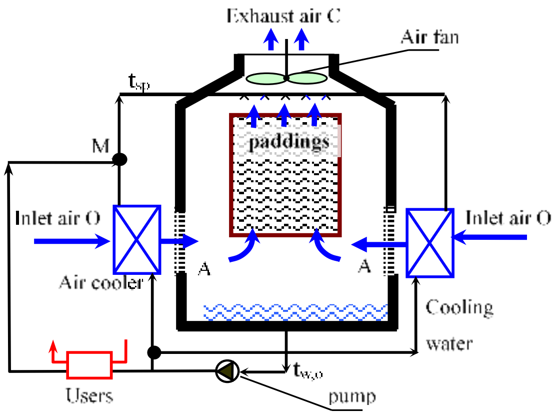
2. Performance analysis of Indirect Evaporative Cooling(IEC) Technologies

Taking indirect evaporative water chiller for example

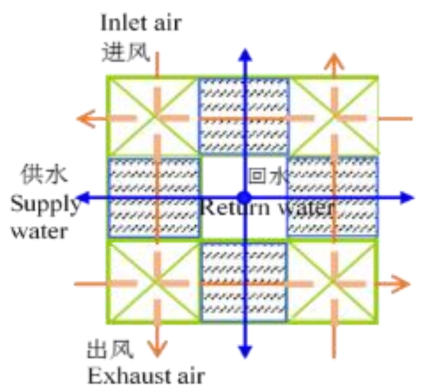
The cooling performance of IEC water chillers

- **The outlet cooling water/air temperature,** determine the feasibility of the application of IEC technologies.
- **The cooling capacity,** analysis the ability to remove indoor sensible heat.

For IEC water chillers, two efficiencies could be used to express the outlet water temperature, the evaporative cooling efficiency and the sensible cooling efficiency



η_{ev}, 0.6~0.8; η_C, 0.7~0.9



η c, 0.3~0.4; η_{ev}, 0.8~0.9

$t_{w,o}=t_{wr}-\boldsymbol{\eta_{ev}}[t_{wr}-(t_{SO}-\boldsymbol{\eta_c}(t_{SO}-t_{dpO})]]$

$\boldsymbol{\eta_c}=(t_{SO}-t_{SA})/(t_{SO}-t_{dpO})$

$\boldsymbol{\eta_{ev}}=(t_{wr}-t_{w})/(t_{wr}-t_{sA})$

Total output cooling energy;

$Q_w=G_w c_{pw}(t_{w,in}-t_{wo})$

Cooling capacity for unit inlet air flow rate；

$q_w=G_w c_{pw}(t_{w,in}-t_{wo})/G_a$

What are the main factors to influence the defined efficiencies?
What about other IEC chiller with different processes?

A unified method is needed to identify and then compare the cooling performance of different IEC processes.

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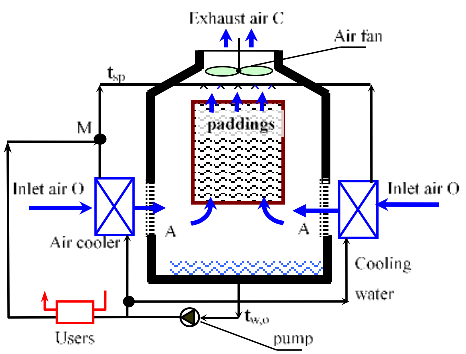
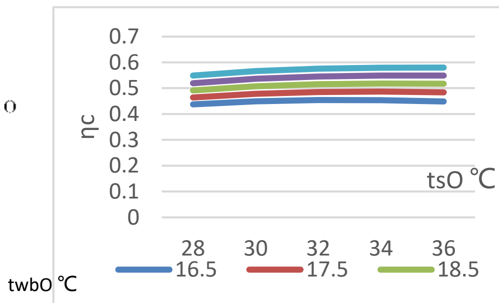
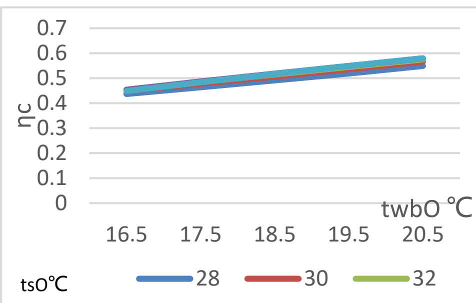
The cooling performance of IEC water chillers

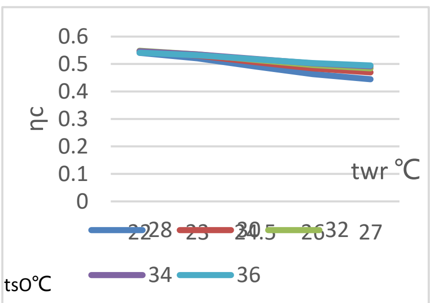
- For the indirect evaporative chiller, the two cooling efficiencies are not constants when inlet air temperature or inlet air humidity ratio changes, which need to be studied further or finally give the rules for the variations.

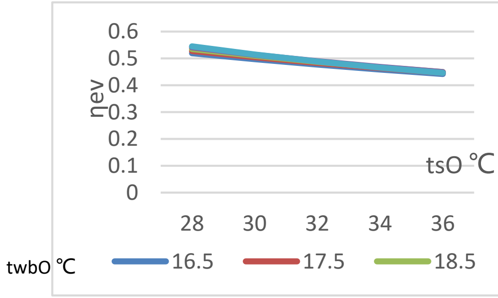


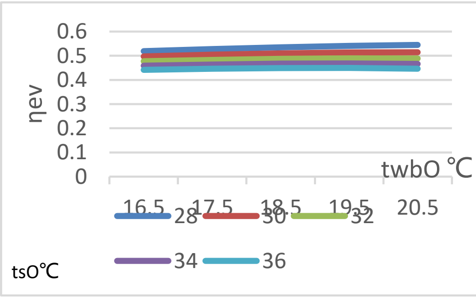
parameter	design value
inlet air dry-bulb temperature t_{sO} ℃	34^{+2}_{-7} ℃
inlet air wet-bulb temperature t_{wbO}	18.5^{+2}_{-2} ℃
returned water temperature t_{wr}	$24.5^{+2.5}_{-2.5}$ ℃
capacity of heat exchanger	$ntu_{ex}=2$
capacity of padding	$ntu_{padding}=1.5$

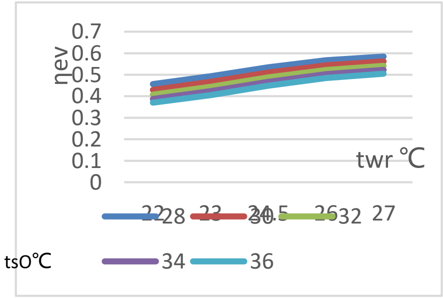




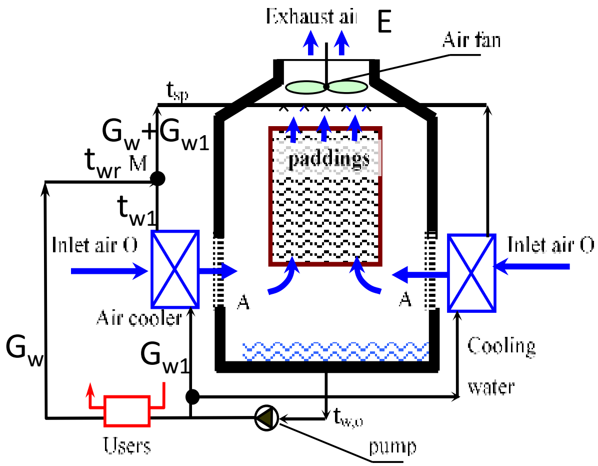




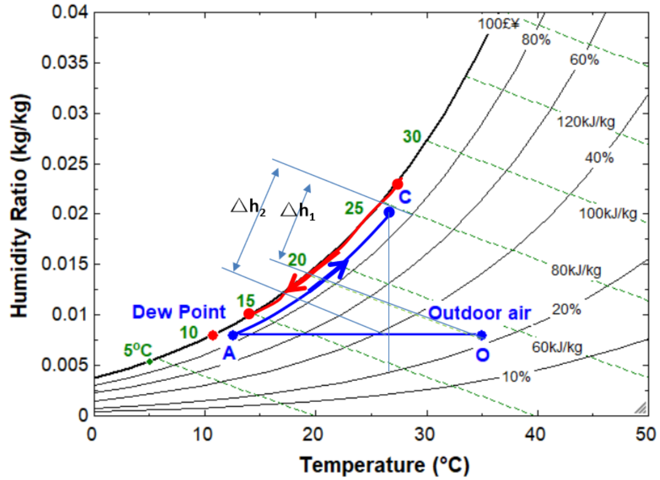




Water consumption performance of IEC water chillers



Air: O→E; Water: t_{wr} →t_w



What is the principal parameter to influence η_w ?

- The higher the exhaust air enthalpy, the higher η_w
- The higher the return water temperature, the higher η_w
- The higher the evaporative cooling efficiency, the higher η_w
- The larger NTU of the tower, the higher η_w

From energy balance, the out put cooling energy:

$$Q_w= G_w c_{pw}(t_{wr}-t_w)=G_a(h_E-h_O)=G_a\Delta h_1$$

The water consumption:

$$W= G_a(d_E-d_O)=G_a\Delta h_2/r_0$$

r_0 : latent heat of vaporization

An efficiency to describe the water consumption could be defined, to identify the effective water consumption:

$$\eta_w= Q_w/r_0 W= \Delta h_1/ \Delta h_2$$

The higher the η_w, the lower the water consumption by water vaporization.

What about different process structure?

The water consumption efficiency could also be used for water vaporization consumption analysis of IEC air coolers.

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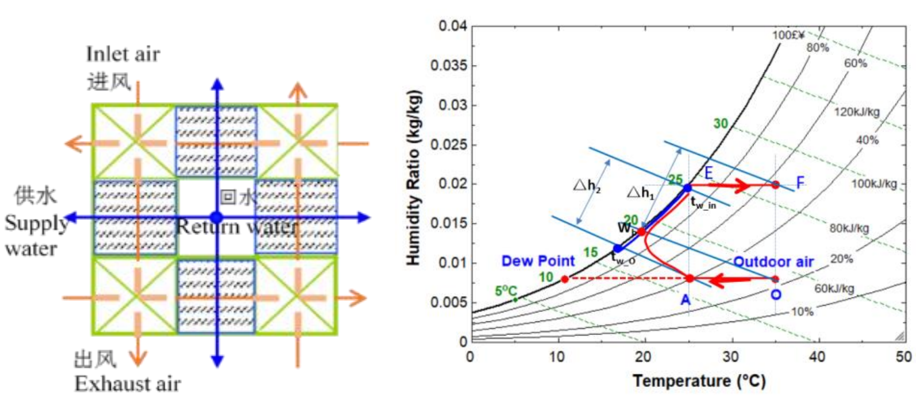
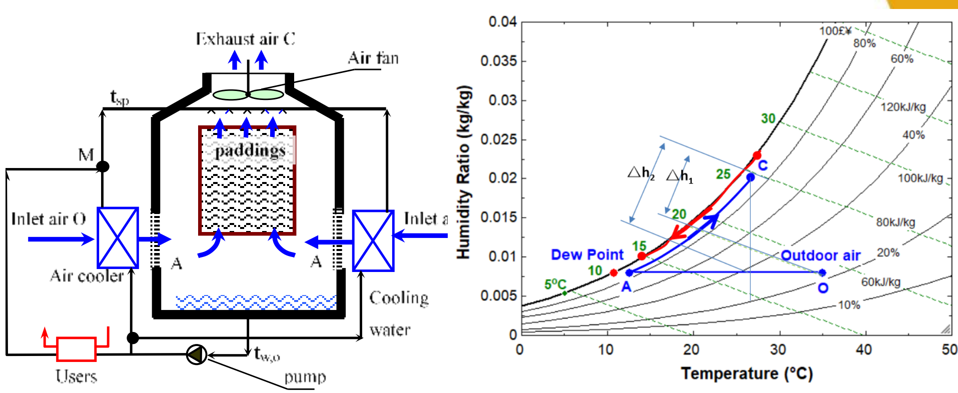
Water consumption of IEC water chillers



Process II



Process I

When totally heat recovery between the inlet air and exhaust air, and the evaporative cooling efficiency equals to one,

$\eta_w = Q_w/r_0 W = \Delta h_1/\Delta h_2 = 1$

Even the sensible cooling efficiency and the evaporative cooling efficiency equals to one,

$\eta_w = Q_w/r_0 W = \Delta h_1/\Delta h_2 < 1$

For the same return water temperature t_{wr} from the users, why the difference of η_w for different processes?

For process I, the sensible cooling process of inlet air O also consume water;

While, for process II, the sensible cooling process is realized by temperature difference and don't need water vaporization

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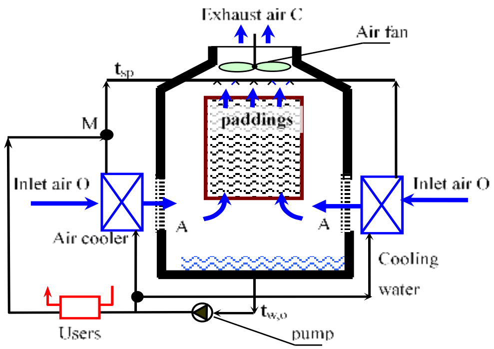
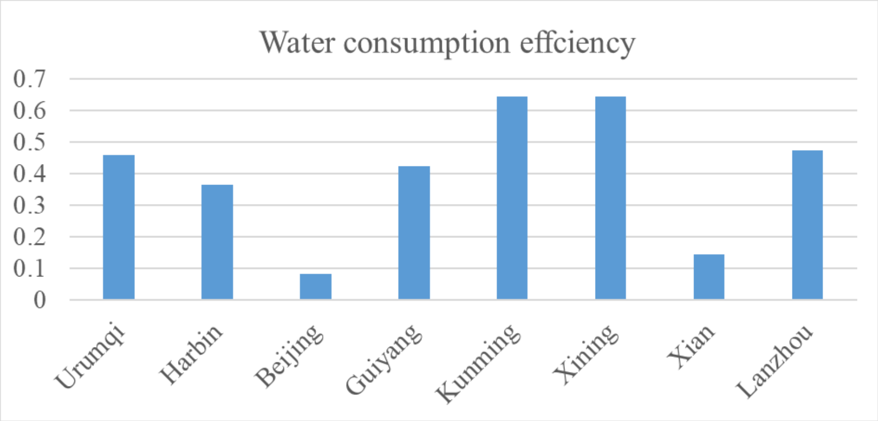
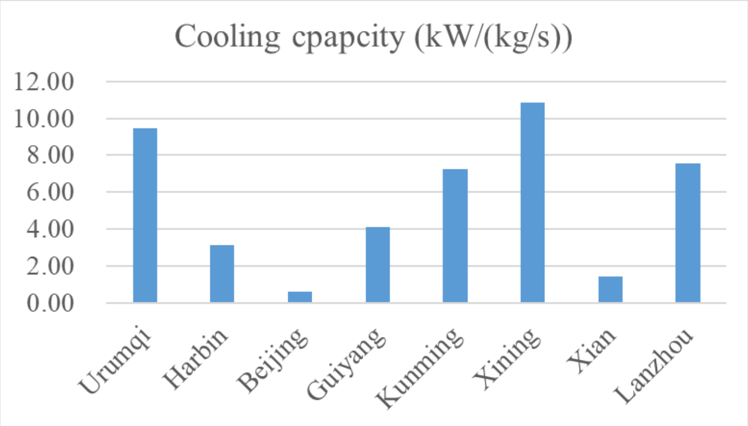
Water consumption of IEC water chillers——A case study

- An example: the water consumption performance of the indirect evaporative chiller(process I) is shown here, the purpose is to remove indoor sensible heat(with indoor temperature set to be 26℃)





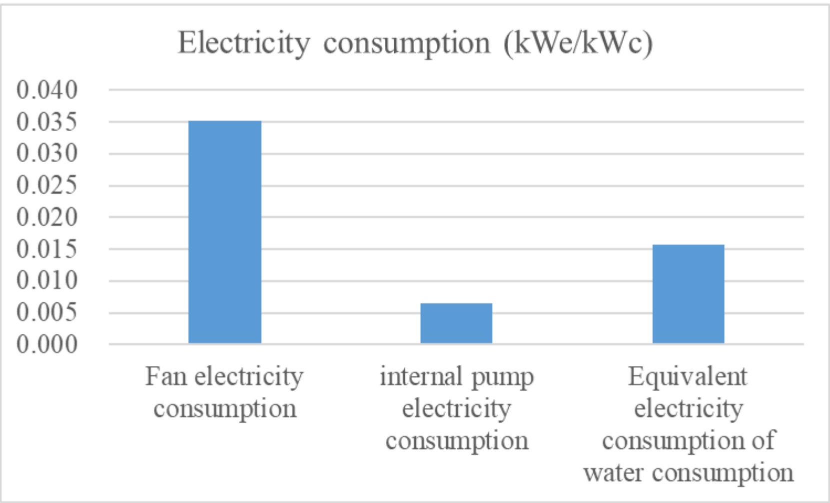


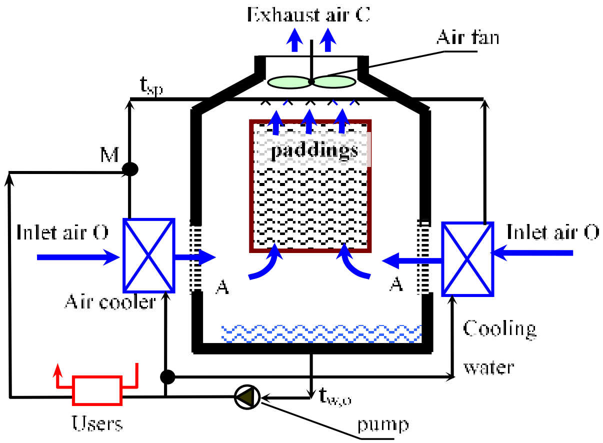
locations	Atmospheric pressure	Dry Bulb Temperature (℃)	Wet bulb temperature (℃)	Out put water temperature(℃)	Return water temperature(℃)	Cooling capapcity (kW/(kg/s))
Urumqi	91.84	33.4	18.3	18.59	22.46	9.47
Harbin	99.62	30.6	23.8	23.54	24.82	3.14
Beijing	101.2	33.6	26.3	25.53	25.78	0.60
Guiyang	89.19	30.1	23	22.78	24.46	4.11
Kunming	81.07	26.3	19.9	20.32	23.29	7.26
Xining	77.41	26.4	16.6	17.5	21.94	10.86
Xian	97.03	35.1	25.8	24.9	25.48	1.40
Lanzhou	84.82	31.3	20.1	20.08	23.17	7.56

The lower the water consumption efficiency, the higher water consumption for the same output cooling energy (the capacity to remove indoor sensible heat), which indicates lower feasibility of using IEC technologies

Water consumption of IEC water chillers——A case study

- Water consumption equivalent to electricity consumption
- When considering the evaporation water is produced by Seawater desalination, and using Membrane method for seawater desalination, with the electricity consumption for producing pure water is 5kWh/m^3, the water consumption could be equivalent to be electricity consumption.





kWe/kWc represents kW electricity consumption per kW cooling energy supply to indoor

For indirect evaporative chiller as an example，under the outdoor design point(91.84 kPa, dry bulb 33.4℃, wet bulb 18.3℃), to remove indoor sensible heat with indoor temperature 26℃, the equivalent electricity consumption of water consumption take about 30% of total electricity consumption, with water consumption efficiency 45.8%.

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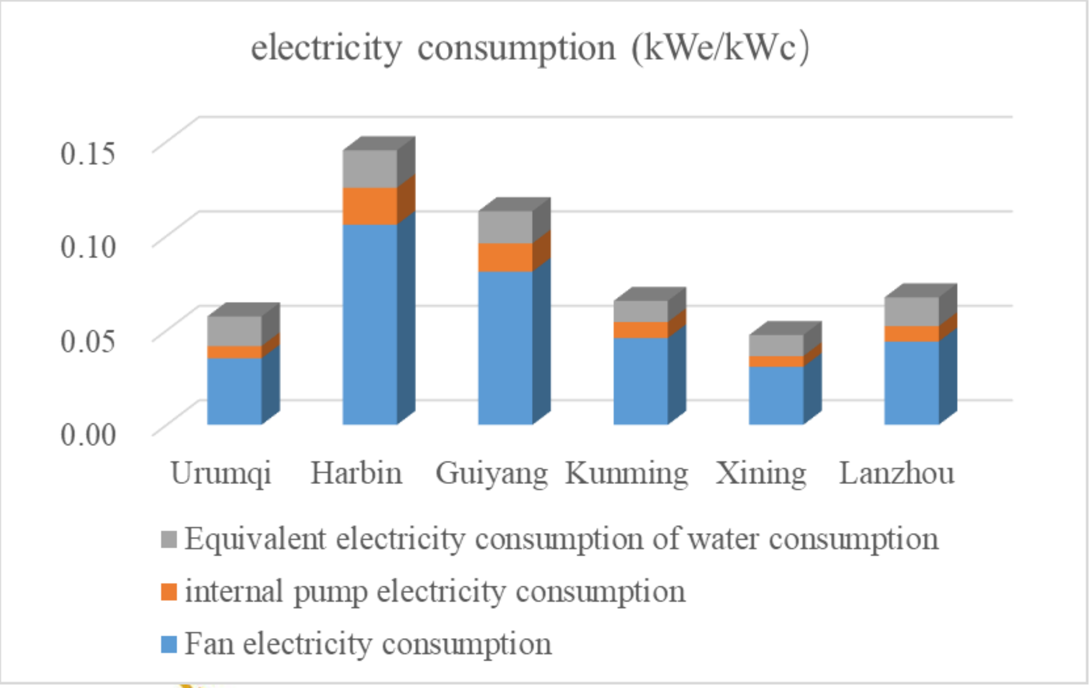
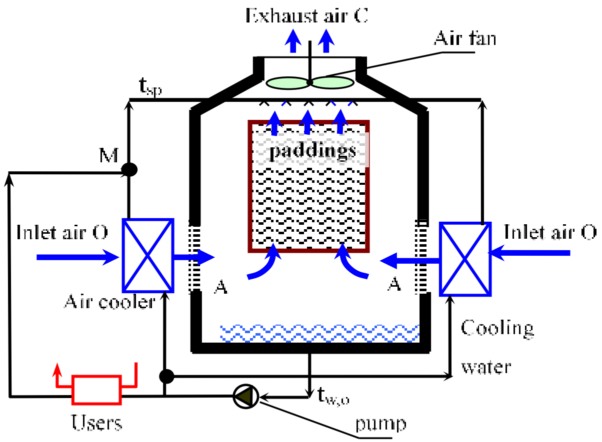
Water consumption of IEC water chillers——A case study

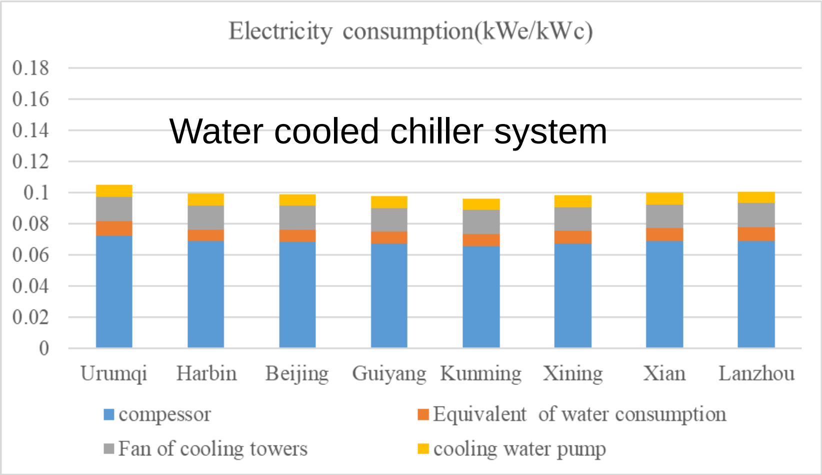
- Combined Water consumption and electricity consumption
- When considering the evaporation water is produced by Seawater desalination, and using Membrane method for seawater desalination, with the electricity consumption for producing pure water is 5kWh/m^3, the water consumption could be equivalent to be electricity consumption.

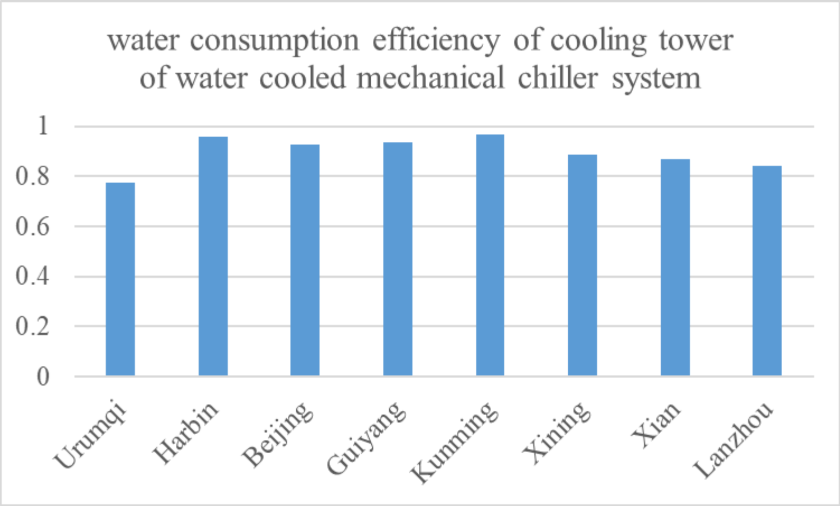


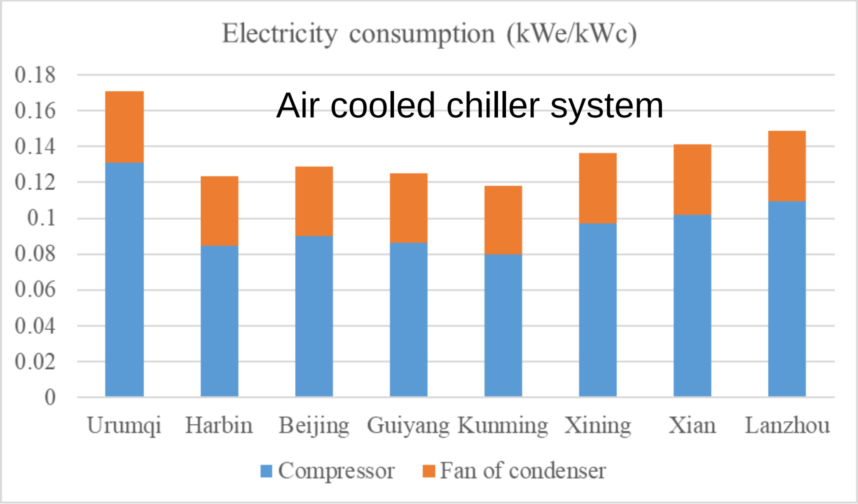


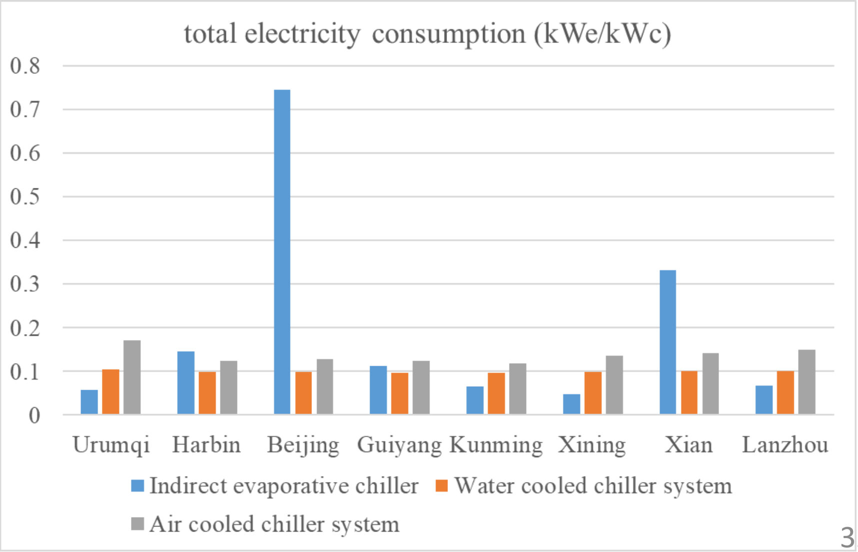
Water consumption of IEC water chillers——A case study

- Combined water consumption and electricity consumption, comparison between common mechanical chiller systems and indirect evaporative chiller systems.









3. Different IEC systems comparison, Different IEC equipment process comparison

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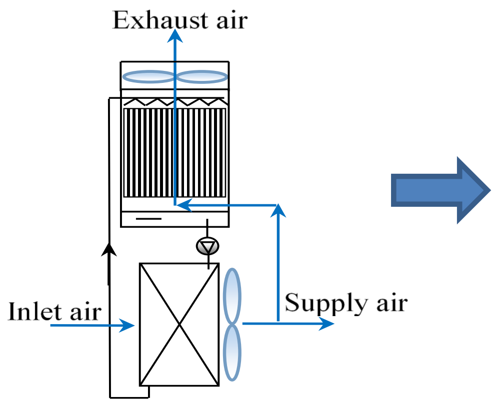
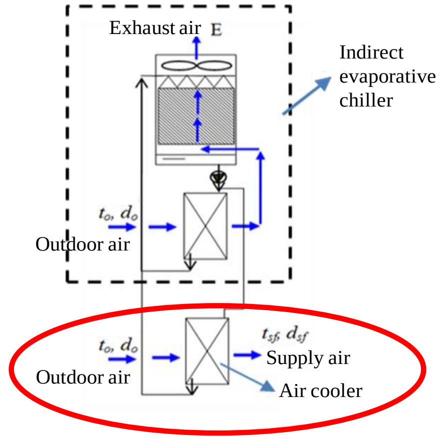
System design, cooling air and cooling water

- For the IEC cooling system to remove indoor sensible heat, choose the IEC cooling air system or IEC water chiller system, which one is better?

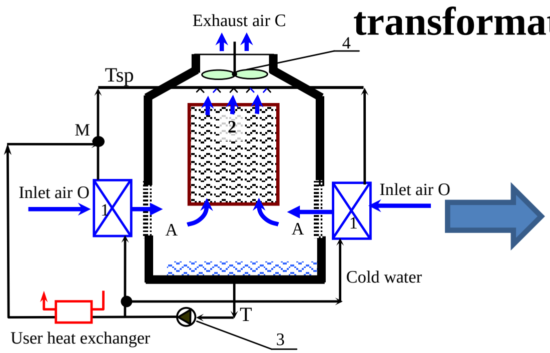
Theoretical research of the process:



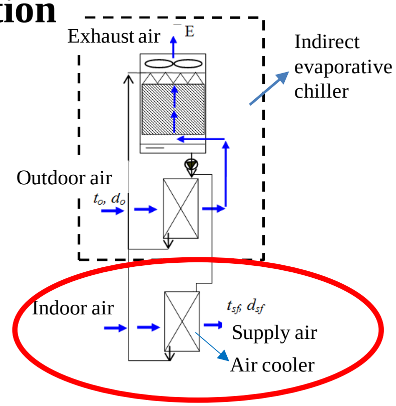
IEC air cooler



processes transformation



IEC water chiller



To remove the same quantity of indoor heat:

- The process produced cooling energy IEC air cooler is larger than IEC water chiller, when outdoor air is hotter than indoor air, the difference is the outdoor air heat load of IEC air cooler.
- Thus, larger heat transfer area and larger cost when using IEC air cooler to remove indoor sensible heat.

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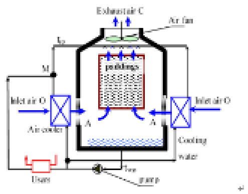
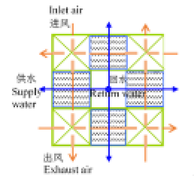
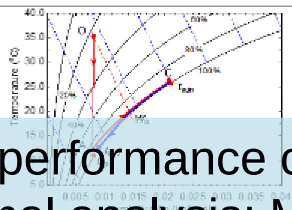
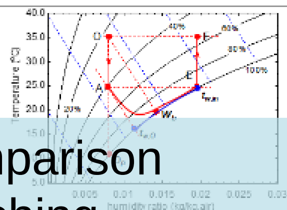
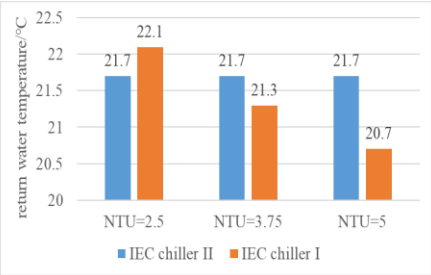
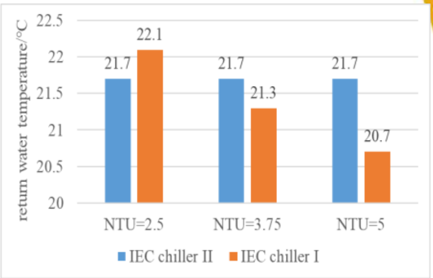
IEC equipment optimization, a case study: comparison of different IEC water chiller processes

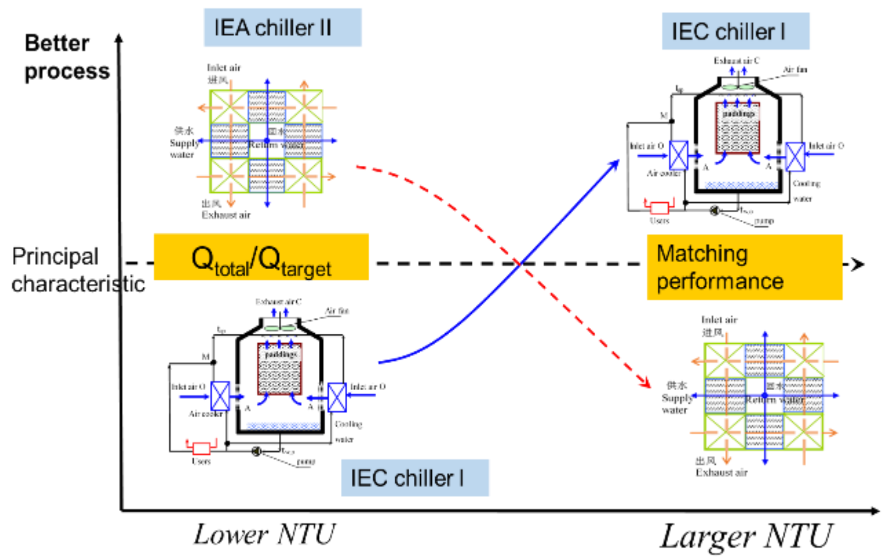
Two different indirect evaporative chiller processes	 IEC chiller process I	 IEC chiller process II
Performance under ideal working conditions: infinite heat transfer area	 The outlet temperature is near outdoor dew point temperature $t_{wo}=t_{dp,o}$; The output cooling energy capacity for unit of inlet air flow rate: $q_{wI}=r_0a(t_{w,in}-t_{dpO})$ Where a represents the slope of the saturation line, a=Δt/Δd; $\frac{Q_{total}}{Q_{target}} = 1 + \frac{c_{pa}}{r_0 a}\left(\frac{t_O - t_{dp,O}}{t_{w,in}-t_{dp,O}} + 1\right)$	 The outlet temperature is higher than outdoor dew point temperature; The output cooling energy capacity for unit of inlet air flow rate: $q_{wII}=r_0a(t_{w,in}-t_{dpO})$ Where a represents the slope of the saturation line, a=Δt/Δd; $\frac{Q_{total}}{Q_{target}} = 1 + \frac{c_{pa}}{r_0 a}\left(\frac{t_O - t_{dp,O}}{t_{w,in}-t_{dp,O}} - 1\right)$
Matching performance	Better than process II; Flow rate matching could be satisfied for each internal process; Inlet parameter matching could be satisfied for evaporative cooling process;	Flow rate matching could be satisfied for each internal process; Inlet parameter matching could be satisfied for evaporative cooling process;
Heat exchange loops: Q_{total}/Q_{target}	Larger than process II	Lower than process I
Mixing Performance	one mixing process of two flows of water with different temperature	no mixing process

- Ideal performance comparison
- Thermal analysis: Matching performance, heat exchange loops, mixing loss;





With the same output cooling energy



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4. Applications of IEC systems, cases in China

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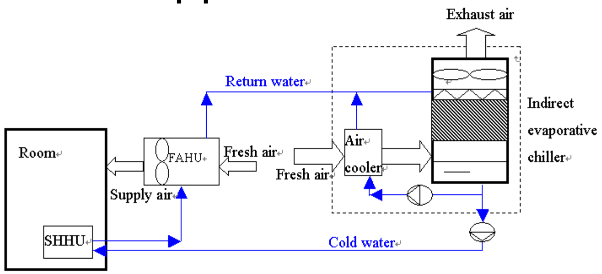
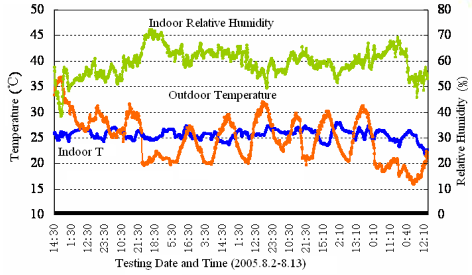
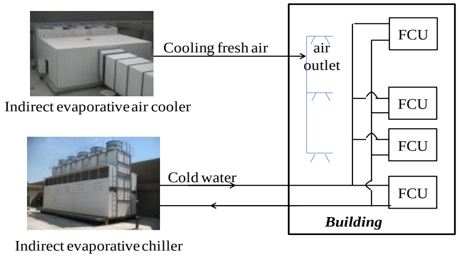
Application of IEC systems, cases in China

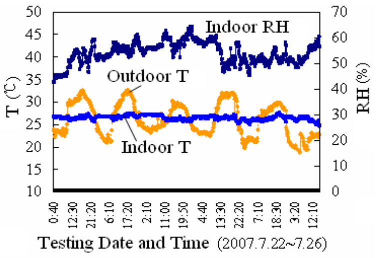
- Different kinds of IEC systems design and optimization and final realized in real applications.



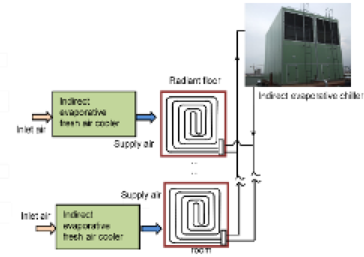


Serial water cycle system using IEC water chiller, with FCUs as terminals.

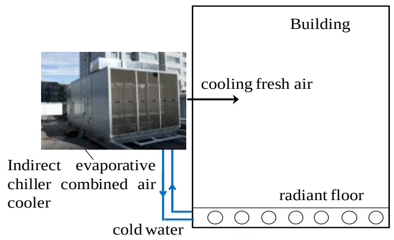


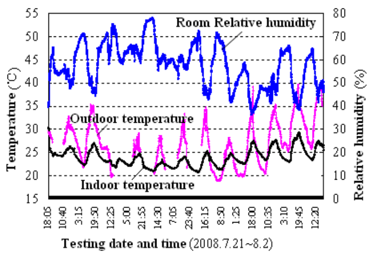


Parallel water cycle system using IEC water chiller, with FCUs as terminals.

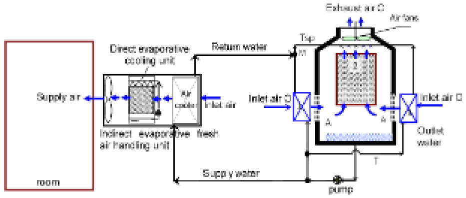


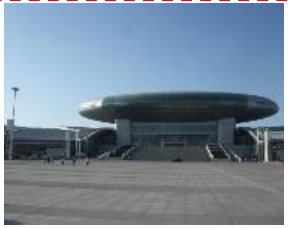
IEC water chiller system using radiant floor as terminals





IEC water chiller combined air cooler system





All fresh air system using IEC water chiller

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Application of IEC systems, cases in China

- IEC water chillers, mainly applied in northwest of China, totally more than 2,000,000m^2, as the cooling source for large public buildings, instead of mechanical chillers.

Shihezi Kairui Hotel，2005，3000m^2;

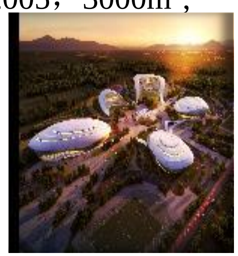
Hospital，2007, 46093 ㎡

International exhibition center，2008~2010, 110767㎡

Hospital ，2009, 25195.6 ㎡

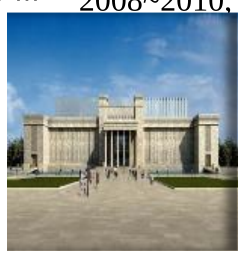
Hospital ，2012, 49200 ㎡

Office building，2014, 7668 ㎡



Sports field，2014, 75146 ㎡

Theater，2015，28654㎡



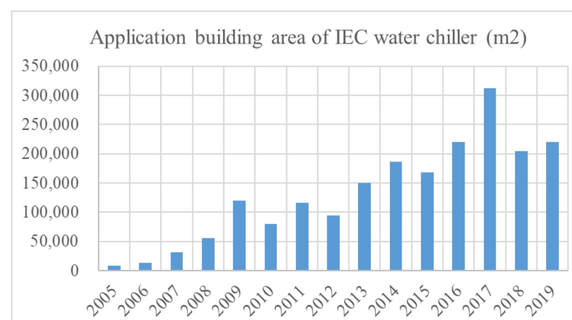
Art Center，2017，78219㎡

Office Building，2015，190000㎡

Detection Building, 2018，452000㎡

High Speed railway station，2015, 99982 ㎡

Industry cooling system



Application of IEC systems, cases in China

- Cases from China, for example
- **Case1：** This is a case of using Indirect Evaporative Chiller in Shihezi city, China, in a hotel building.
- Building area, 3000m^2, from 2005 to now

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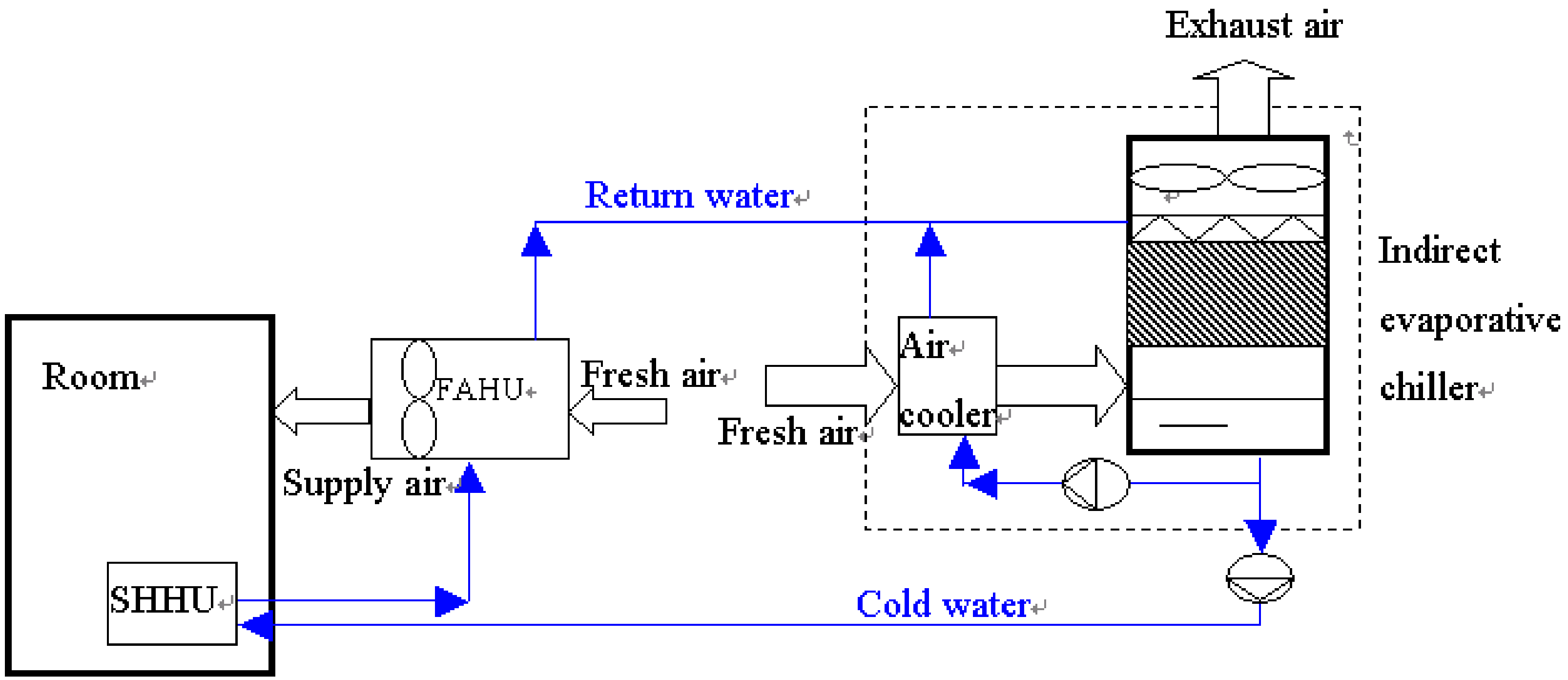
Application of IEC systems, cases in China

- **Case1：** Shihezi Kairui Building, Xinjiang, China, a hotel building, with building area 3000m^2, from 2005 to now.
- **System principle** : using serial system structure, with fan coil units as terminals to remove sensible heat, indirect evaporative chiller to produce cold water, indirect evaporative fresh air handling unit to produce cooling air with humidity ratio as dry as outdoor conditions.



Application of IEC systems, cases in China

- **Case1：** Shihezi Kairui Building, Xinjiang, China, a hotel building, with building area 3000m^2, from 2005 to now.

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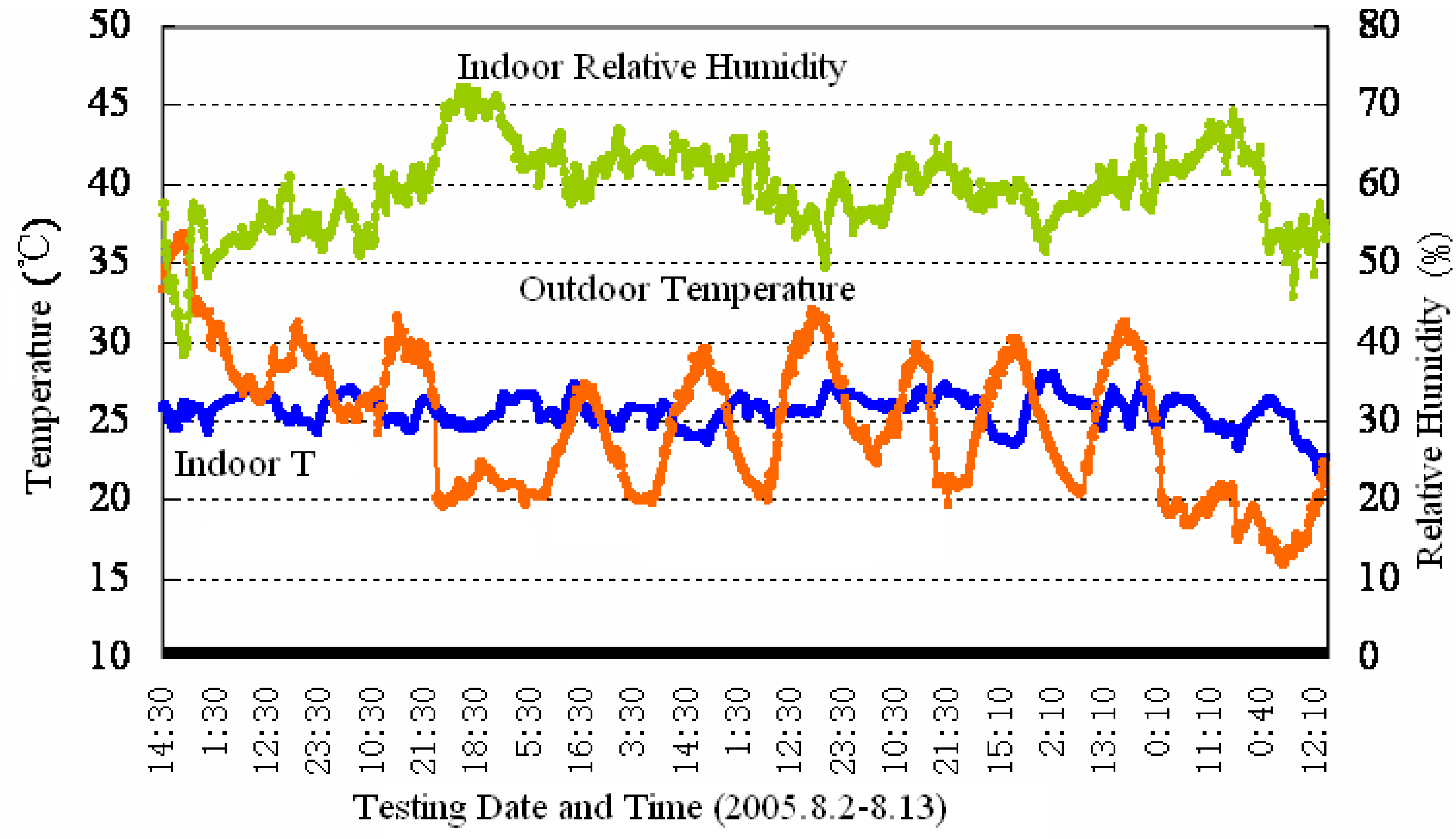
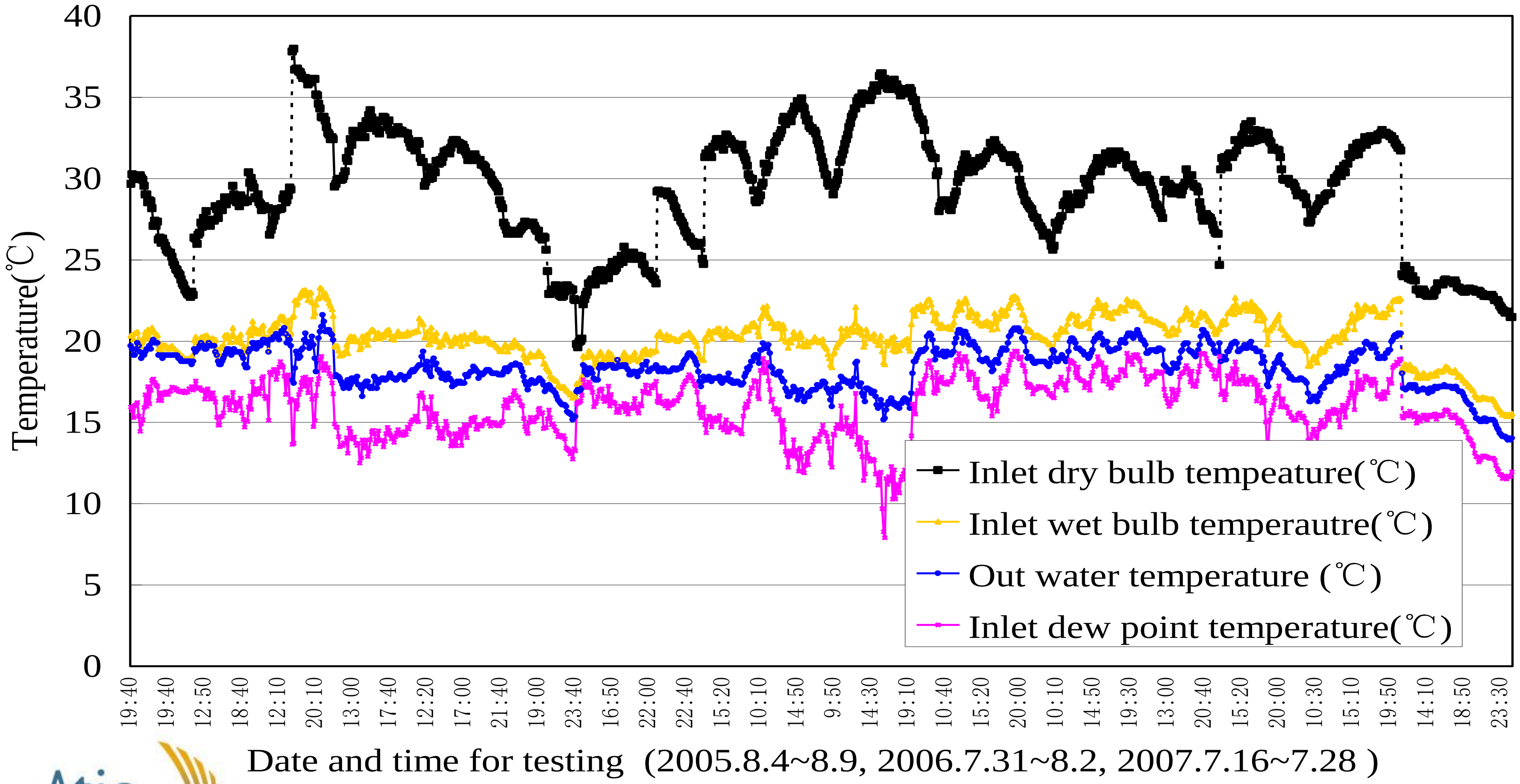
Application of IEC systems, cases in China

- **Case1:** Shihezi Kairui Building, Xinjiang, China, a hotel building, with building area 3000m^2, from 2005 to now.
- Testing performance of indoor air conditions.



Application of IEC systems, cases in China

- **Case1:** Shihezi Kairui Building, Xinjiang, China, a hotel building, with building area 3000m^2, from 2005 to now.
- Testing performance of the indirect evaporative chiller.



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Application of IEC systems, cases in China

- **Case 2**: using Indirect Evaporative Chiller in Urumqi city, China, in a hospital building, with dry fan coil units as sensible terminals.
- **Xinjiang Traditional Medicine Hospital (13000m^2) , from 2007 to now**

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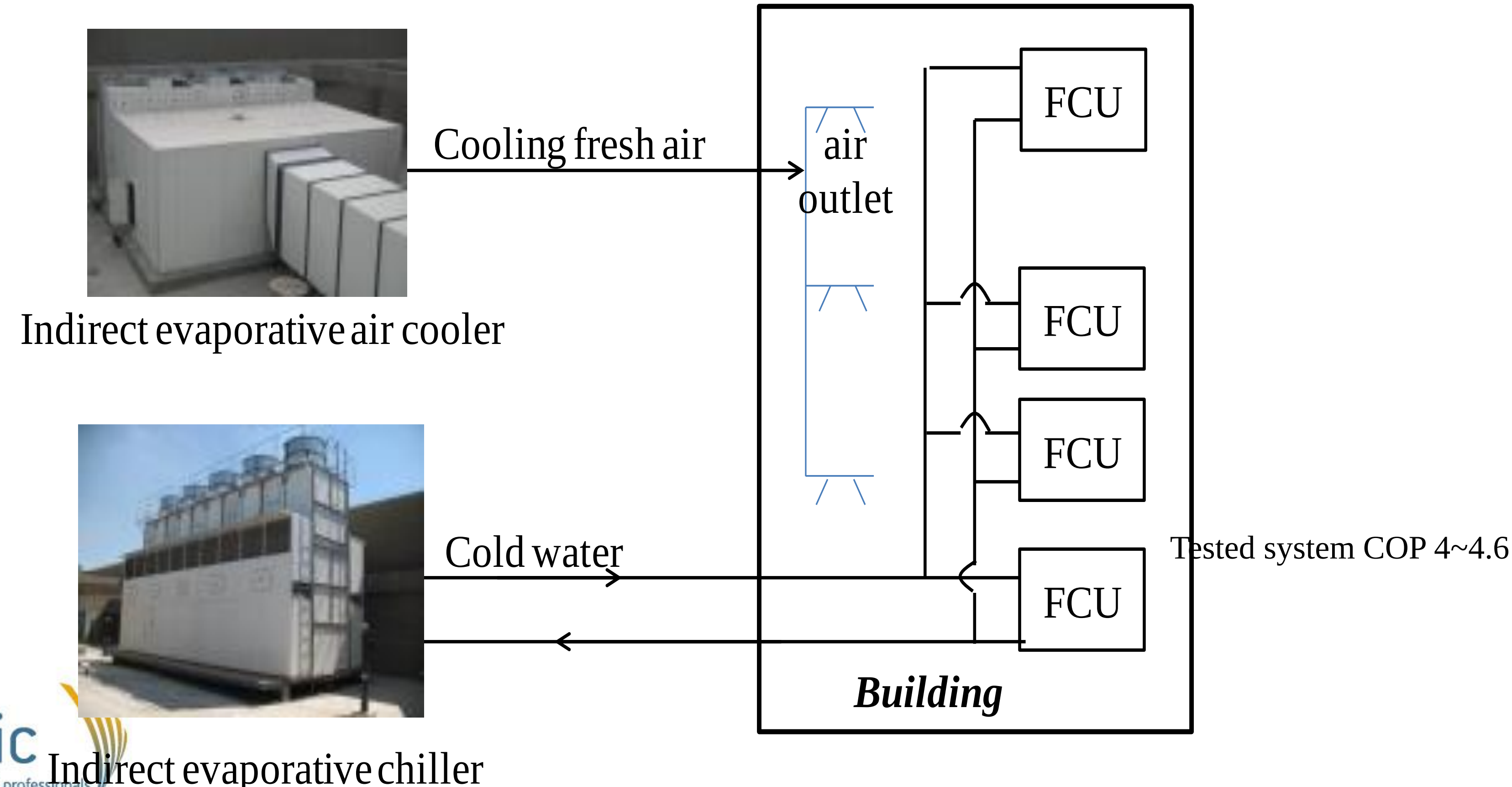
Application of IEC systems, cases in China

- **Case 2**: Xinjiang Traditional Medicine Hospital (13000m^2) , from 2007 to now
- **System principle:** With fan coil units as terminals to remove sensible heat, indirect evaporative chiller to produce cold water, and indirect evaporative fresh air handling unit to produce cooling air with humidity ratio as dry as outdoor conditions.



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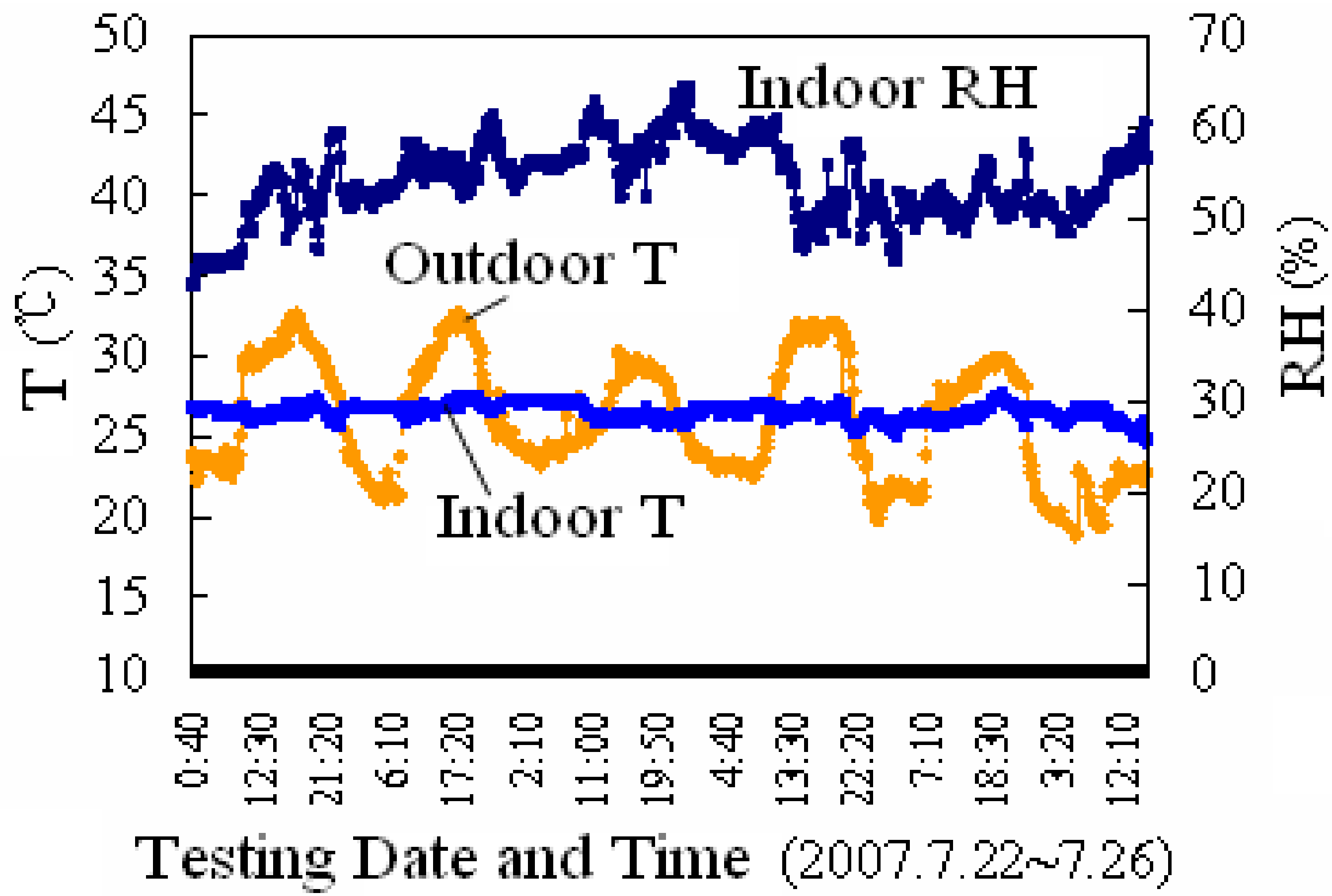
Application of IEC systems, cases in China

- **Case 2**: Xinjiang Traditional Medicine Hospital (13000m²) , from 2007 to now
- **Testing performance:** indoor air conditions..



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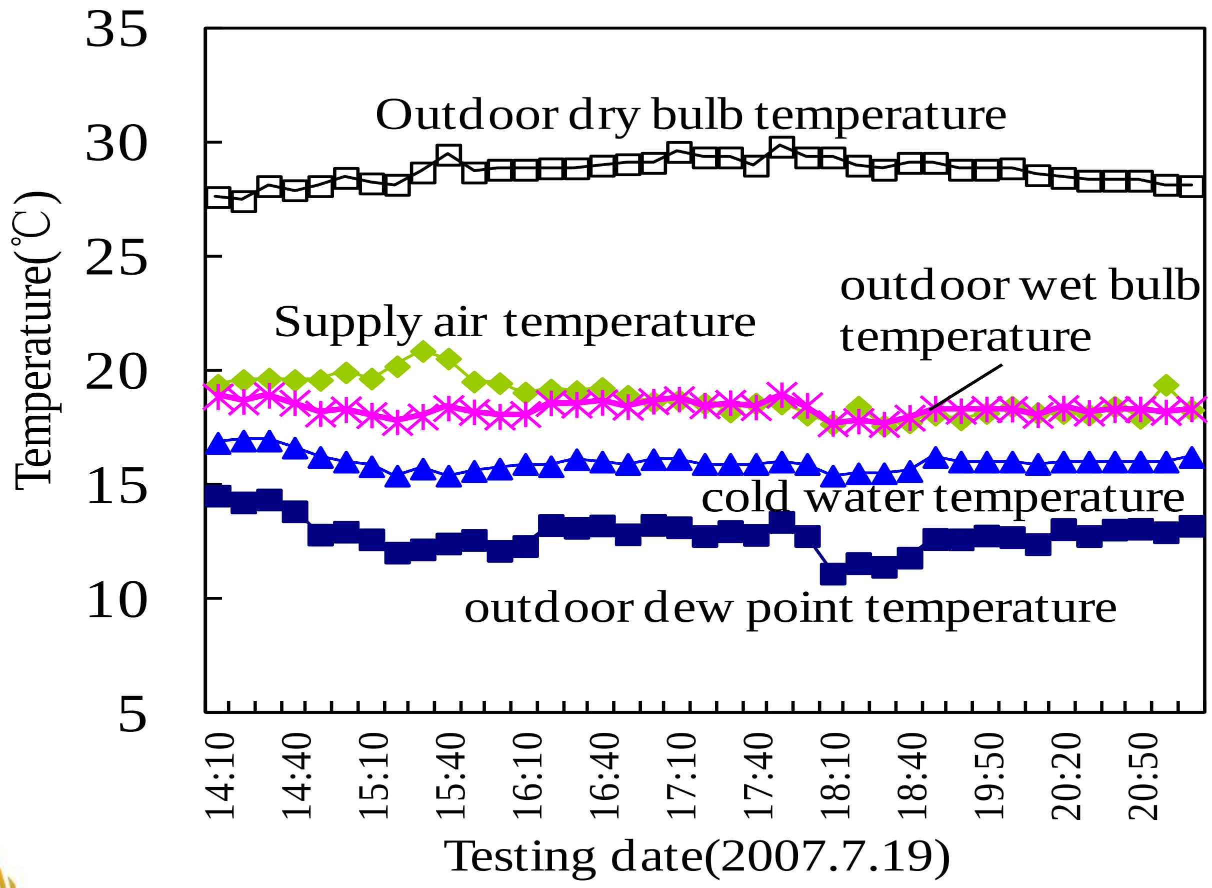
Application of IEC systems, cases in China

- **Case 2**: Xinjiang Traditional Medicine Hospital (13000m^2) , from 2007 to now
- **Testing performance** of the indirect evaporative water chiller..

Tested system COP 4~4.6



Application of IEC systems, cases in China

- **Case 3**: using Indirect Evaporative Chiller in Urumqi city, China, in a hospital building, with radiant floor as sensible heat terminals.
- Urumqi Air Force hospital (17231.4m^2) (from 2009 to now)

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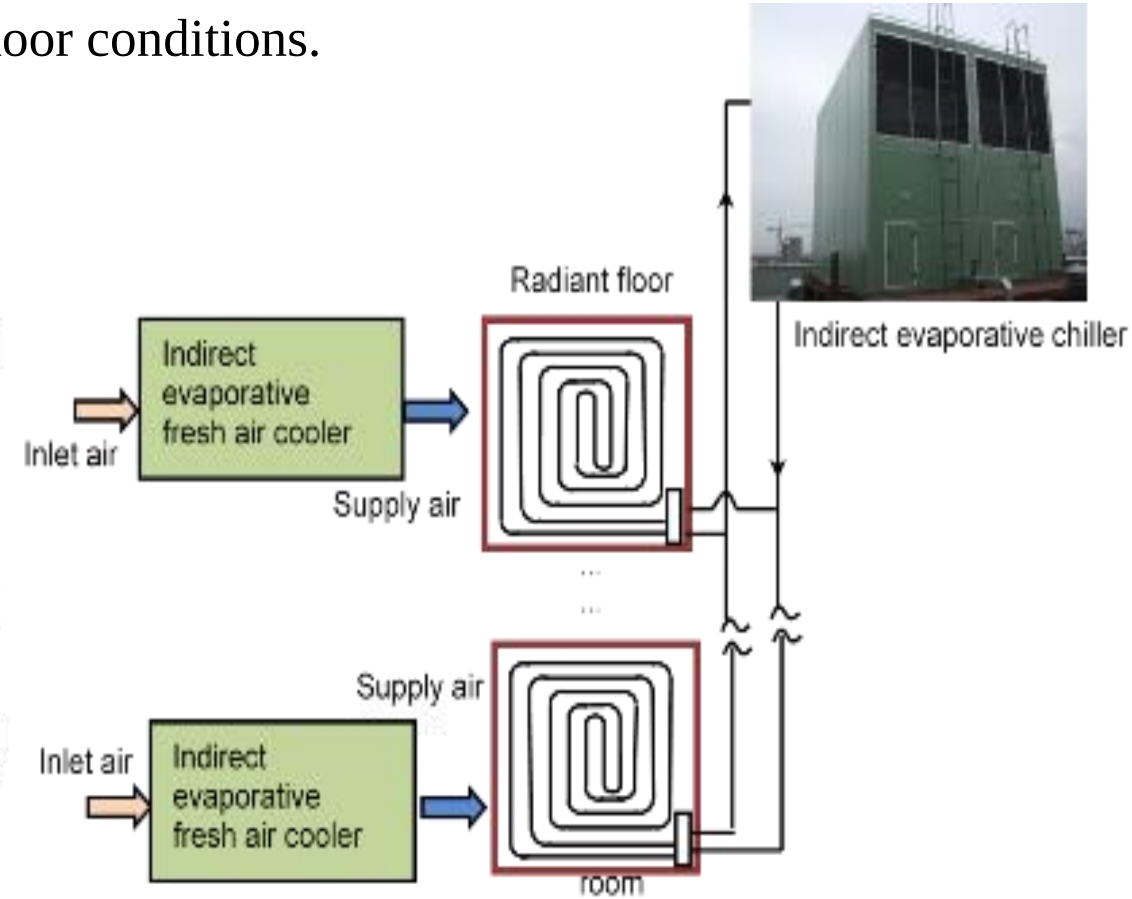
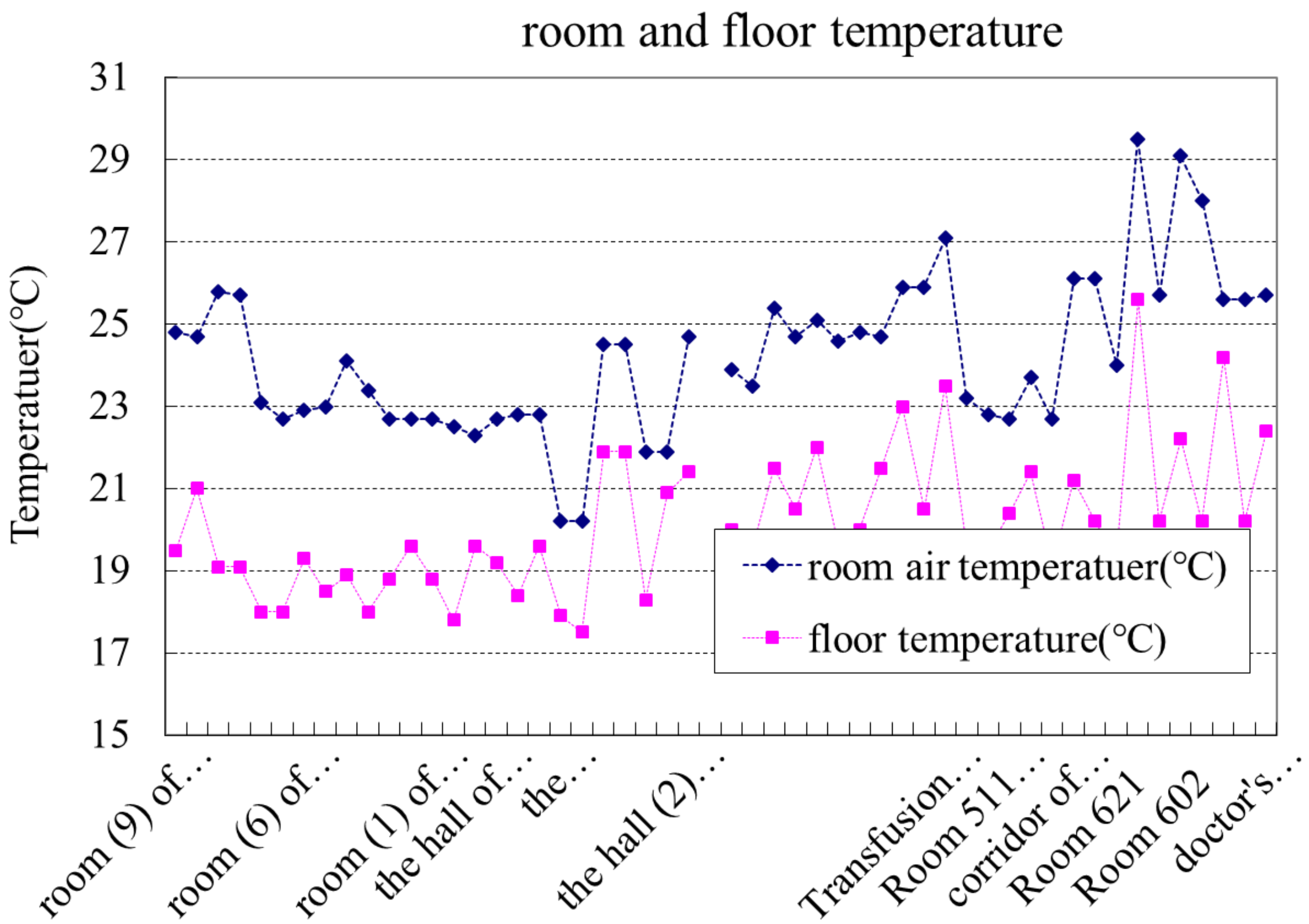
Application of IEC systems, cases in China

- **Case 3**: Urumqi Air Force hospital (17231.4m^2) (from 2009 to now)
- **System principle:** With radiant floor as terminals to remove sensible heat, using indirect evaporative chiller to produce cold water and indirect evaporative fresh air handling unit to produce cooling air with humidity ratio as dry as outdoor conditions.



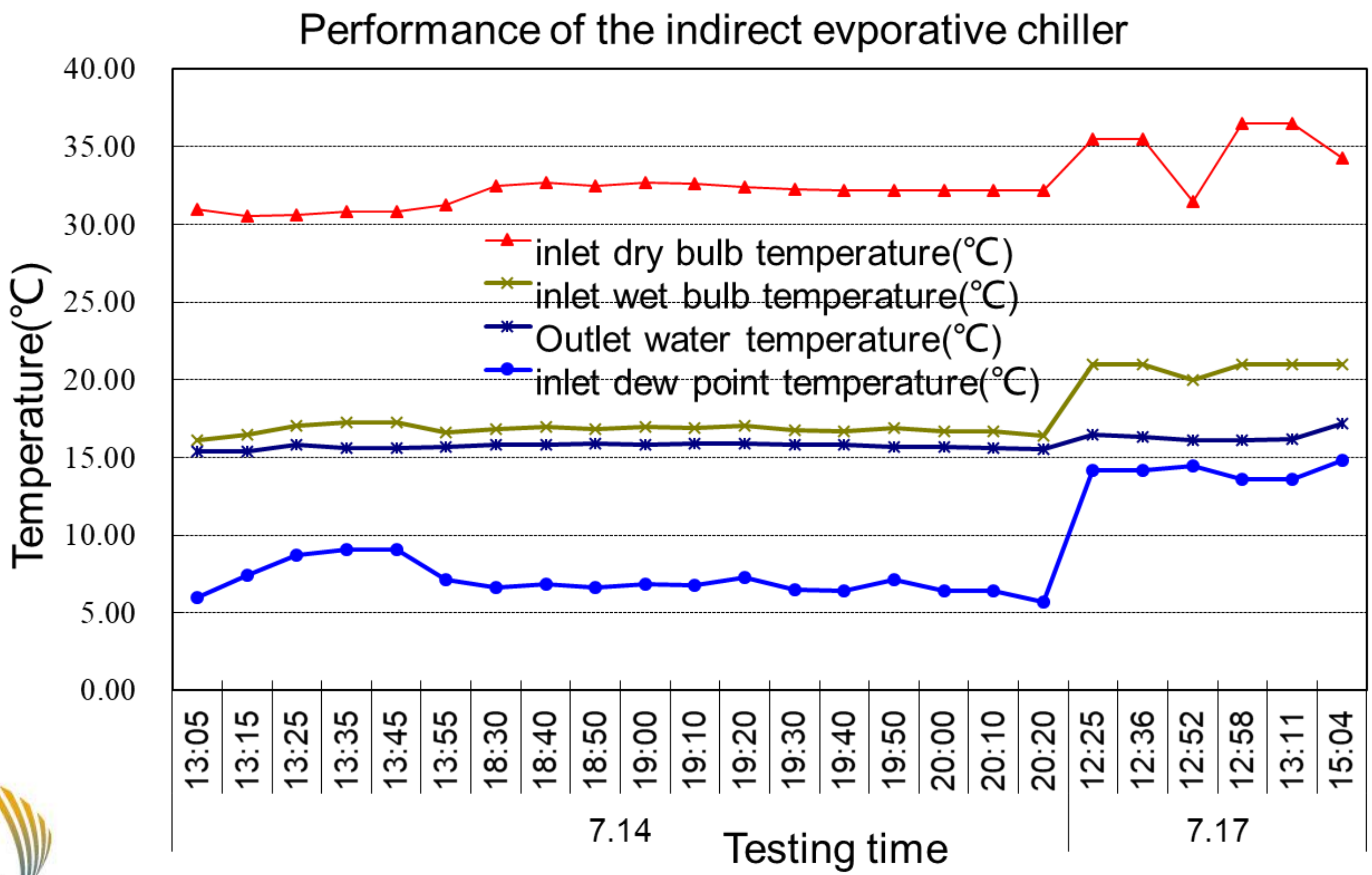
Application of IEC systems, cases in China

- **Case 3**: Urumqi Air Force hospital (17231.4m^2) (from 2009 to now)
- **Testing performance:** indoor air conditions.



Application of IEC systems, cases in China

- **Case 3**: Urumqi Air Force hospital (17231.4m^2) (from 2009 to now)
- **Testing performance:** the indirect evaporative water chiller.
- Tested system COP 5~6.



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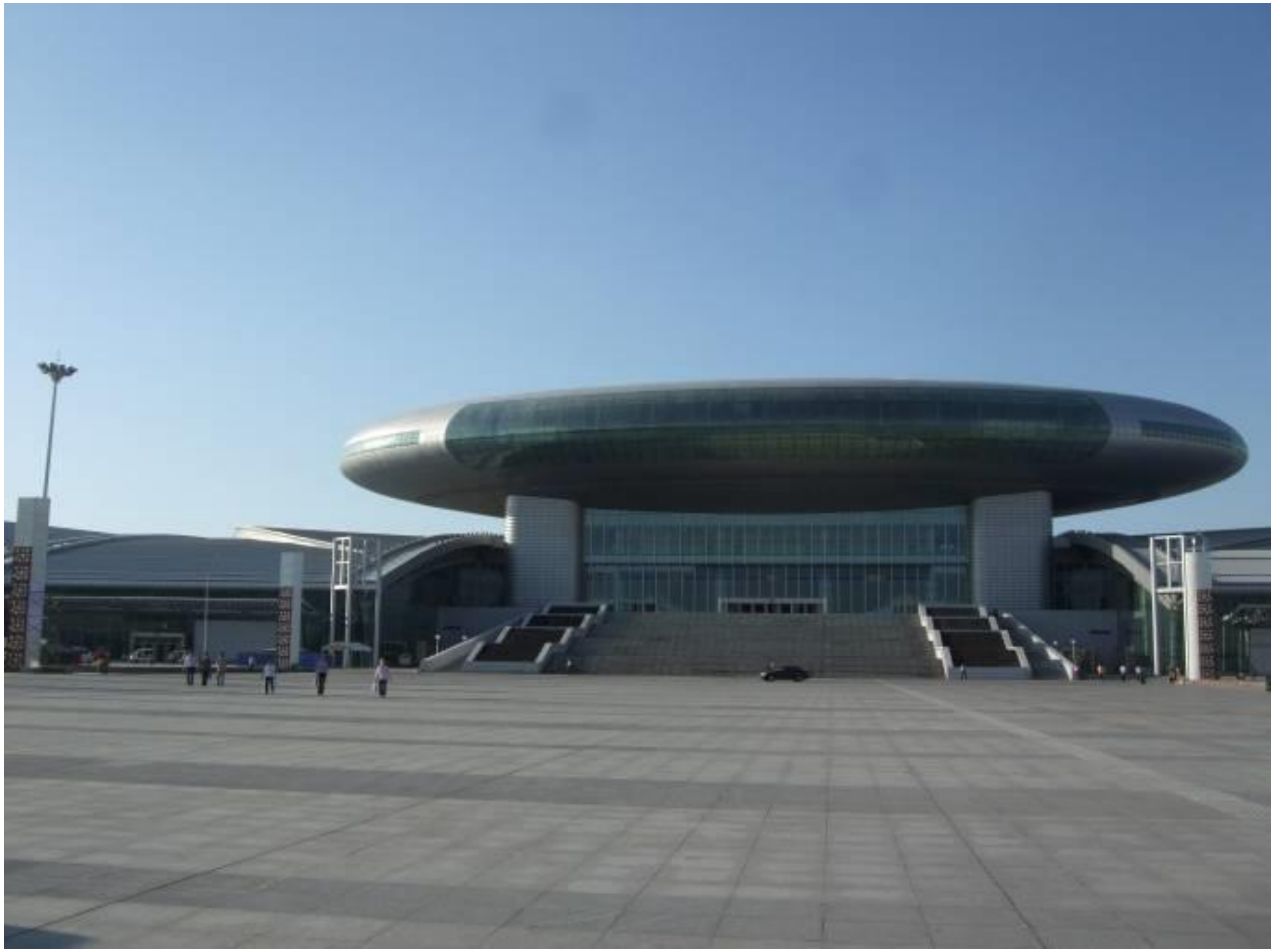
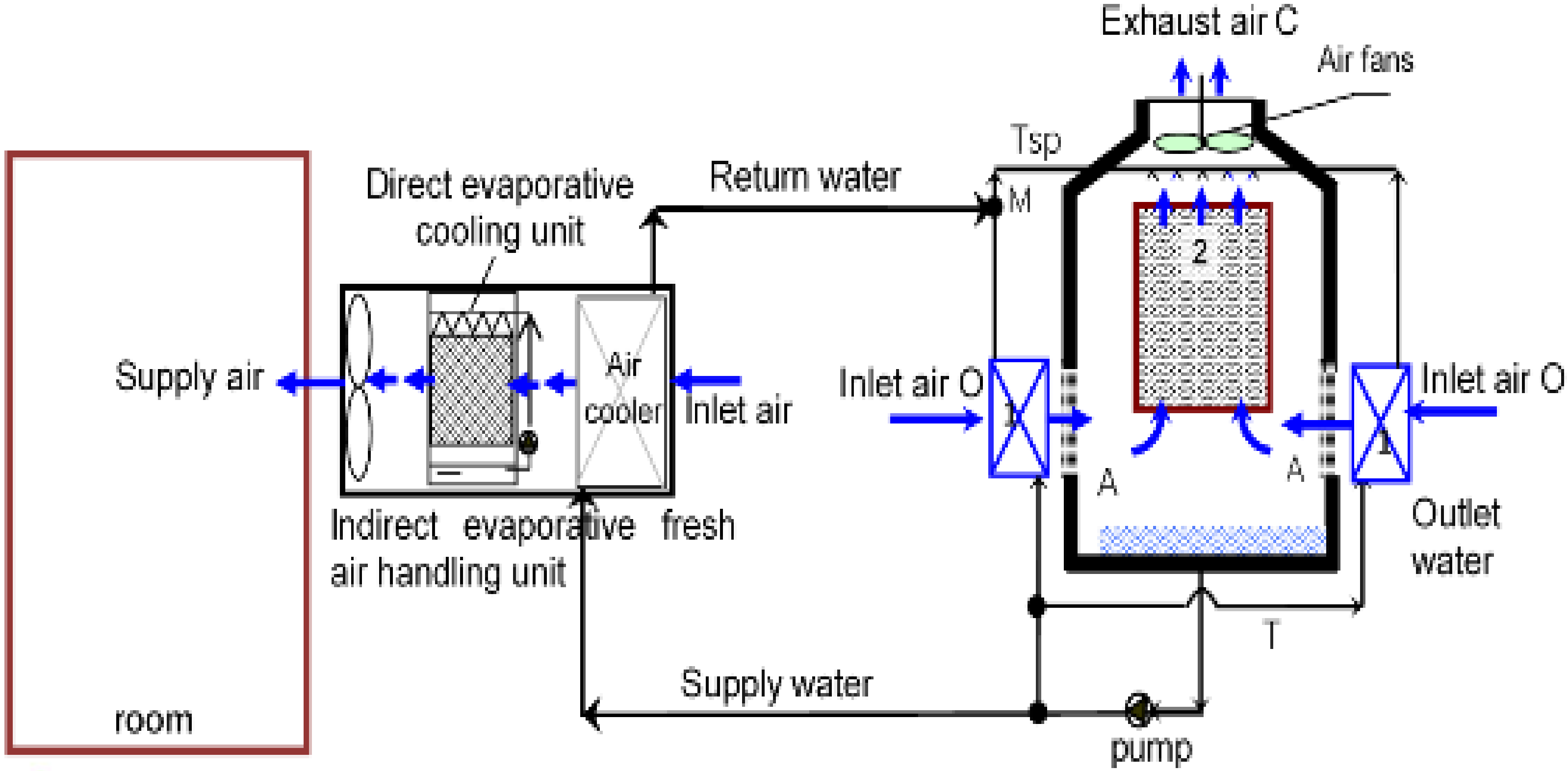
Application of IEC systems, cases in China

- **Case 4**: using Indirect Evaporative Chiller in Urumqi city, China, in a exhibition building, with Fresh air handling Units as sensible heat terminals.
- Xinjiang international exhibition center (100,000m^2) (from 2010 to now)



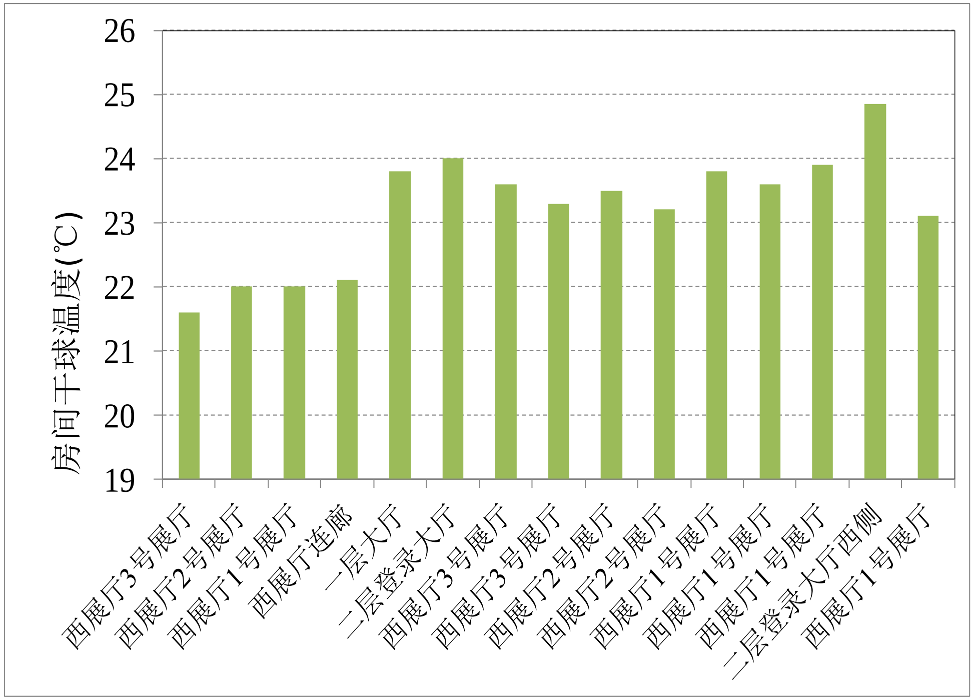
Application of IEC systems, cases in China

- **Case 4**: Xinjiang international exhibition center (100,000m²) (from 2010 to now)
- **System principle:** All fresh air system, with indirect evaporative chillers as the cooling source for the fresh air handling units, to produce cooling fresh air to supply to buildings.

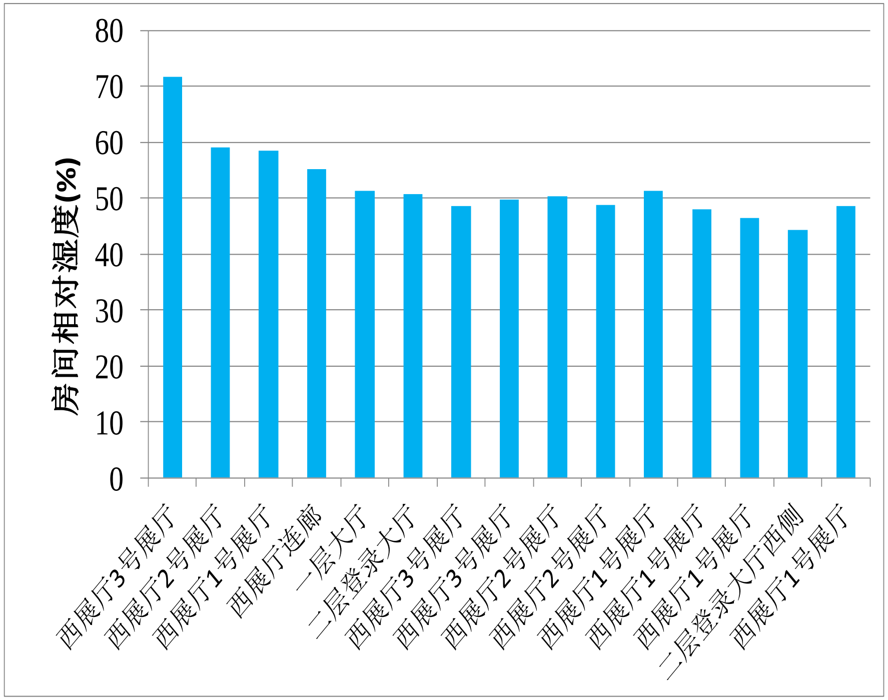


Application of IEC systems, cases in China

- **Case 4**: Xinjiang international exhibition center (100,000m^2) (from 2010 to now)
- **Testing performance:** indoor air conditons
- Tested system COP 3.5~4



Indoor air temperature



Indoor air relative humidity

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Application of IEC systems, cases in China

- **Case 5**: using Indirect Evaporative Chiller in Urumqi city, China, in a railway station, with radiant floors as sensible heat terminals.
- Xinjiang High speed railway station (100,000m^2) (from 2014 to now).

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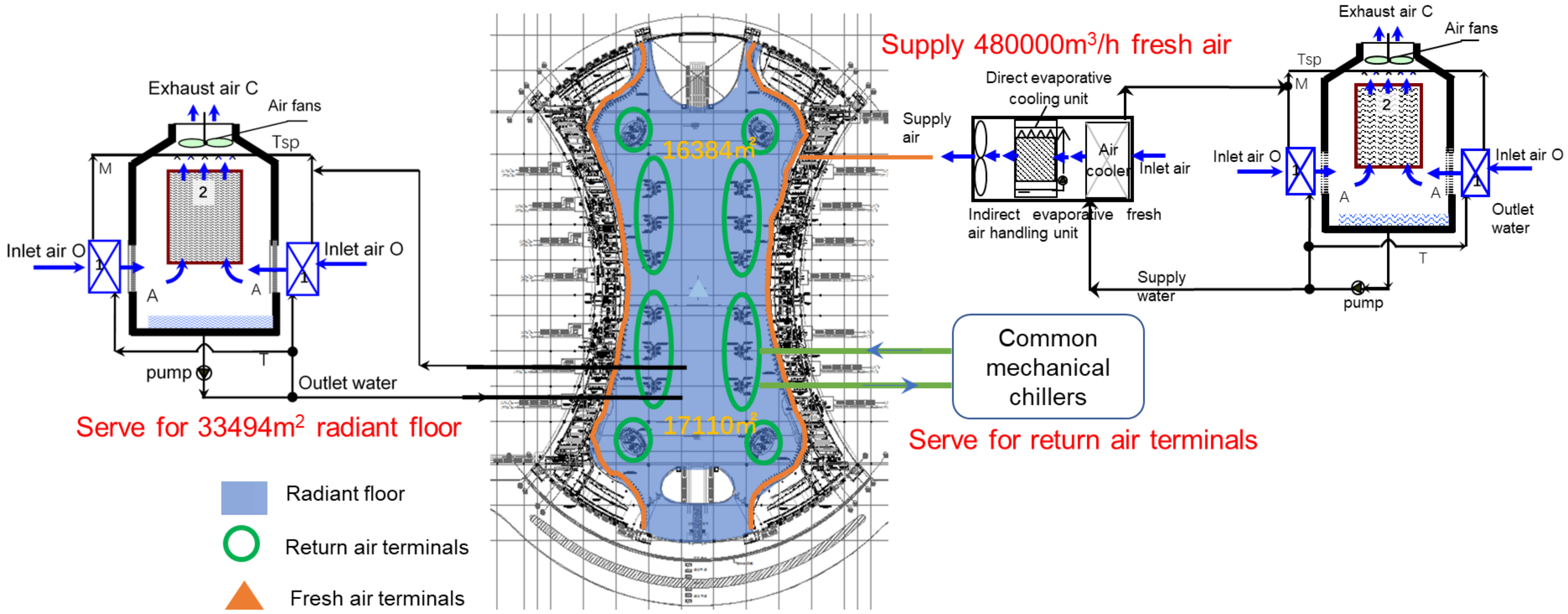
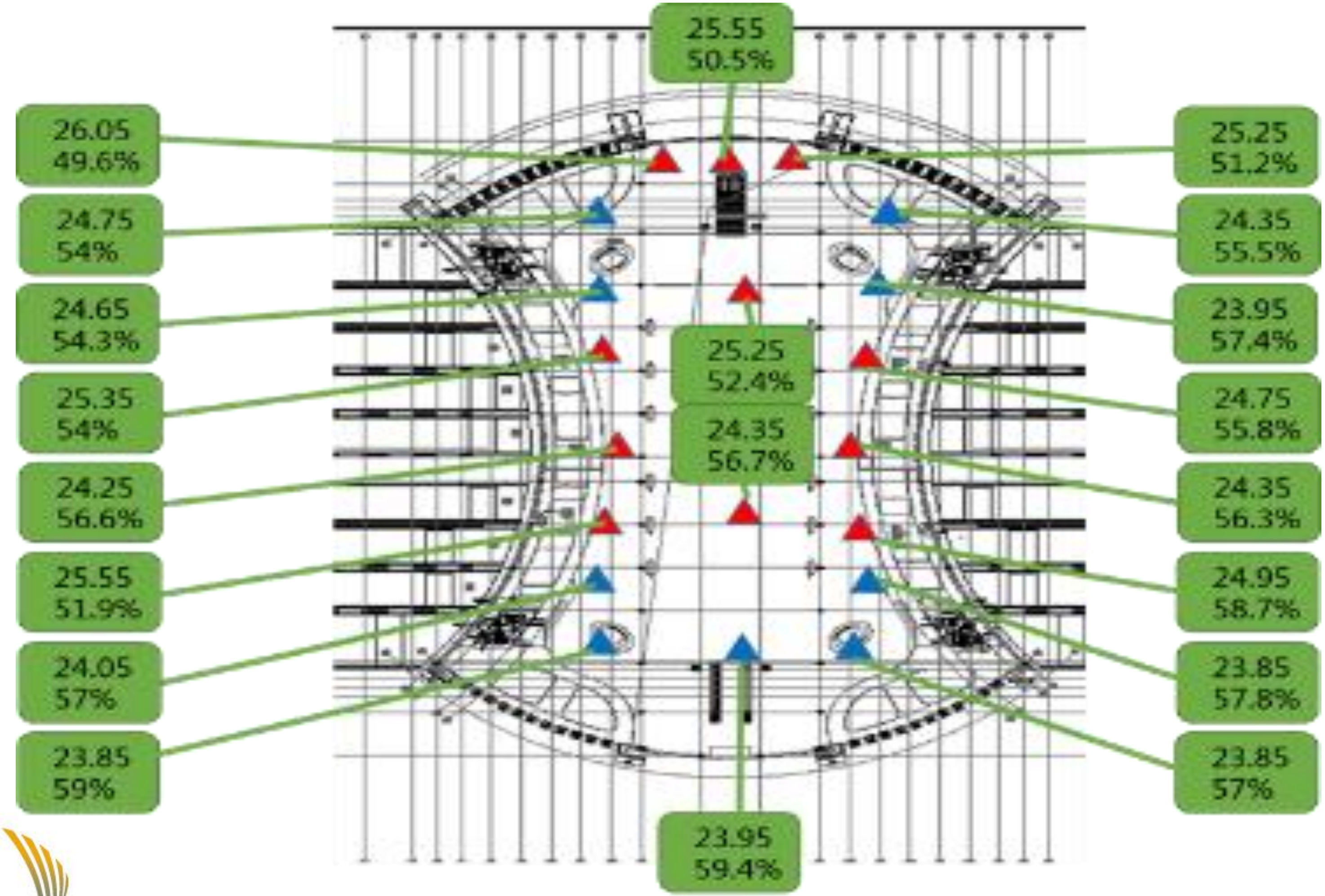
Application of IEC systems, cases in China

- **Case 5**: Xinjiang High speed railway station (100,000m^2) (from 2014 to now).
- **System principle:** Using indirect evaporative chillers to produce cold water to serve for 33494m^2 radiant floor, using indirect evaporative chillers to produce cold water to cool fresh air with 48000m3/h, using mechanical chiller to produce cold water for large fan coil units.



Application of IEC systems, cases in China

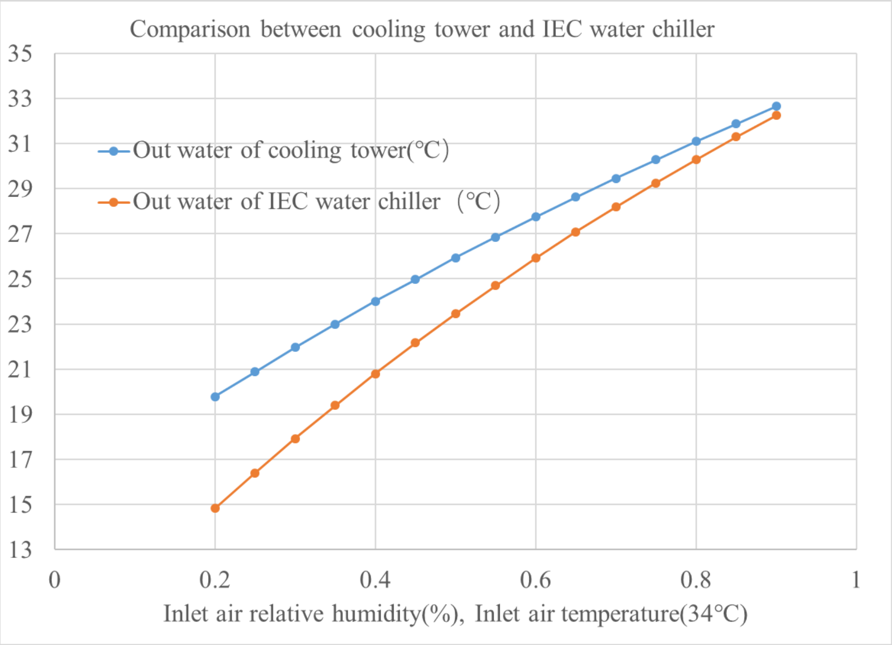
- **Case 5**: Xinjiang High speed railway station (100,000m^2) (from 2014 to now).
- **Testing performance:** indoor air conditions.

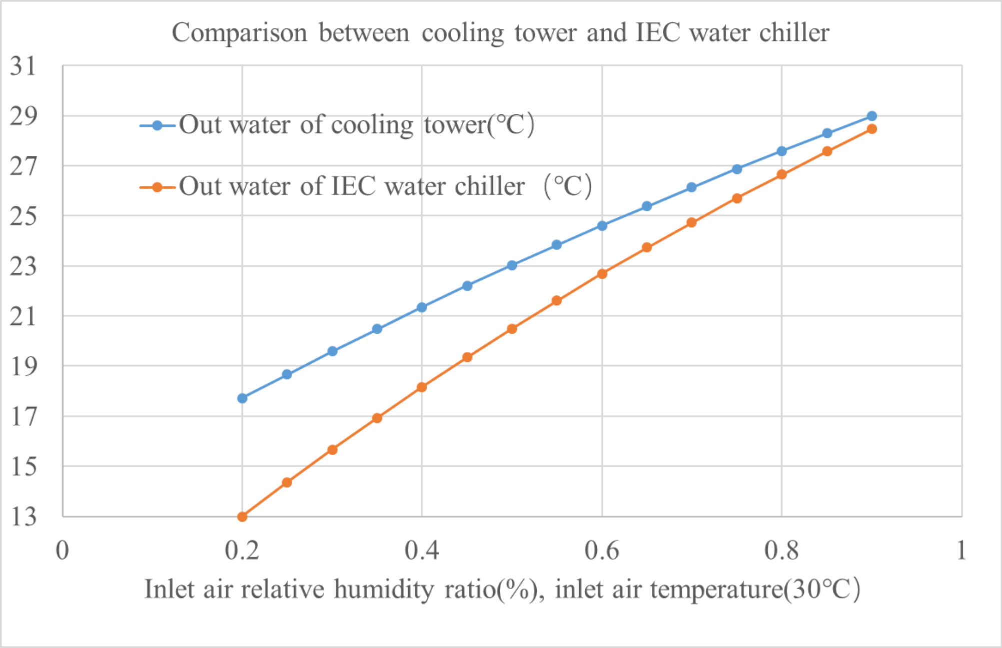


5. Feasibility study of IEC water chillers

Comparison with cooling towers at different outdoor relative humidity

- Compared with DEC processes, IEC processes are suitable for dry climates with relative humidity low enough, the higher the relative humidity, the less the difference between DEC processes.





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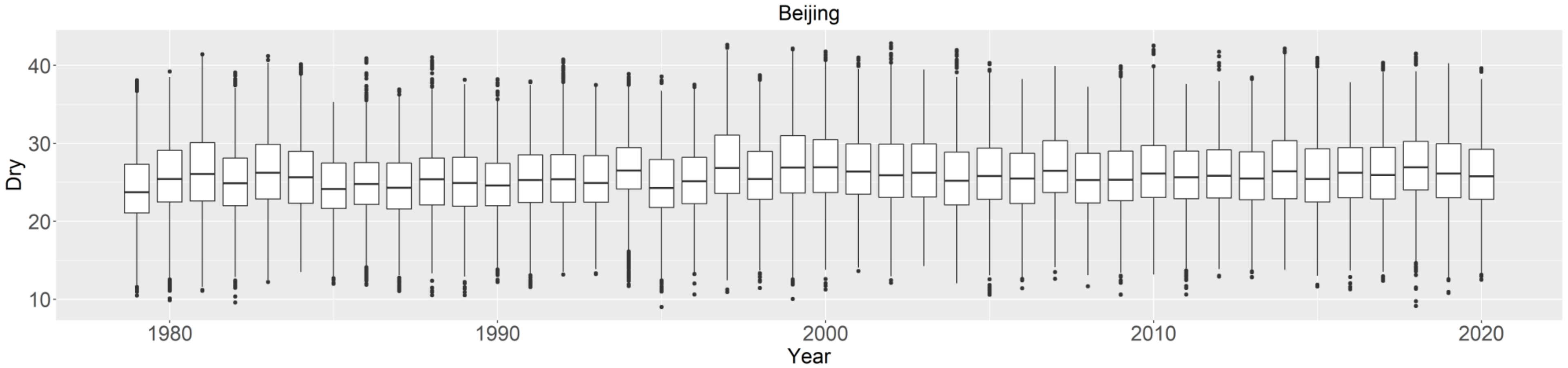
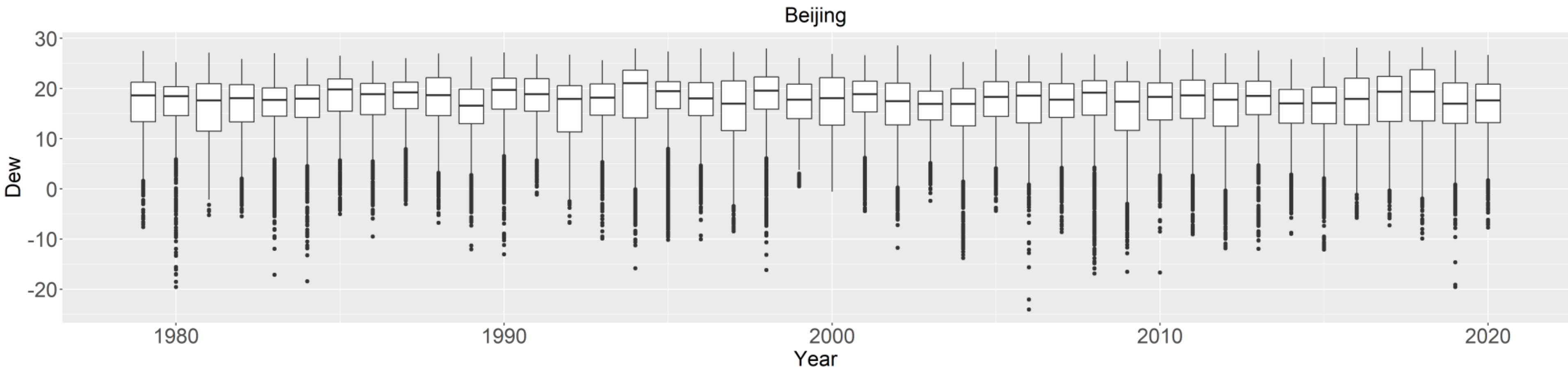
Feasibility study of IEC water chillers using in typical cities

- Bejing, China, average outdoor conditions in summer





Feasibility study of IEC water chillers using in typical cities

- Bejing, China, outdoor air conditions in 2020 summer

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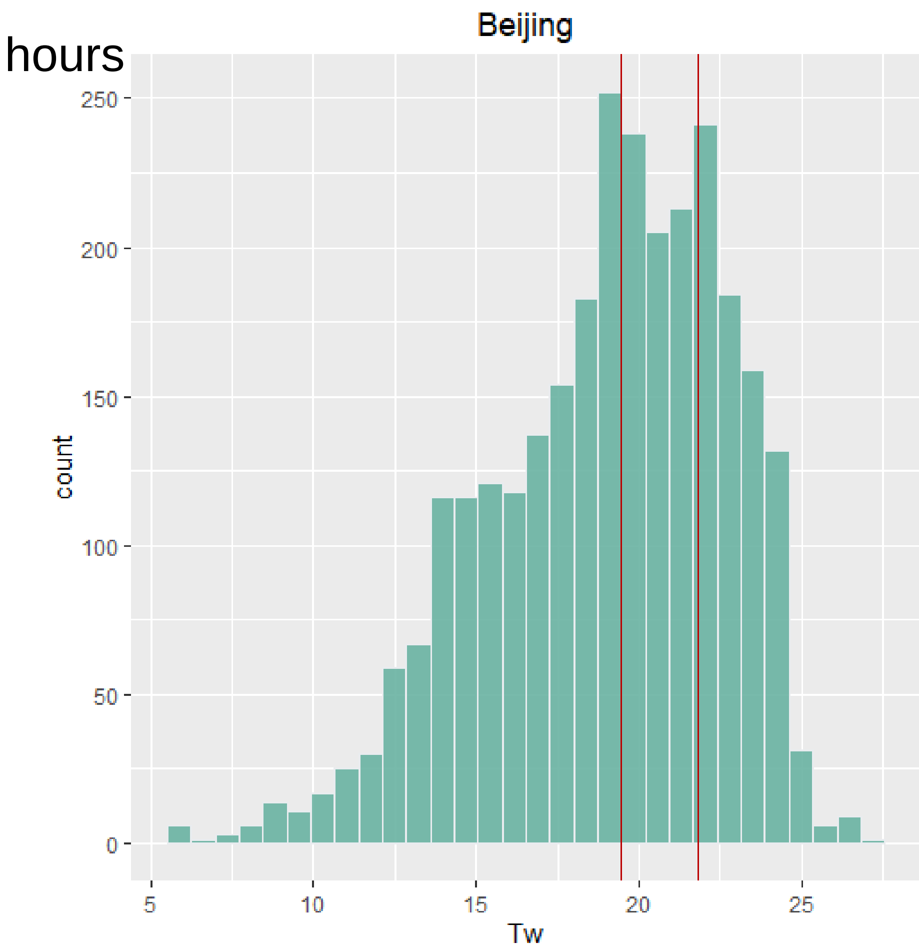
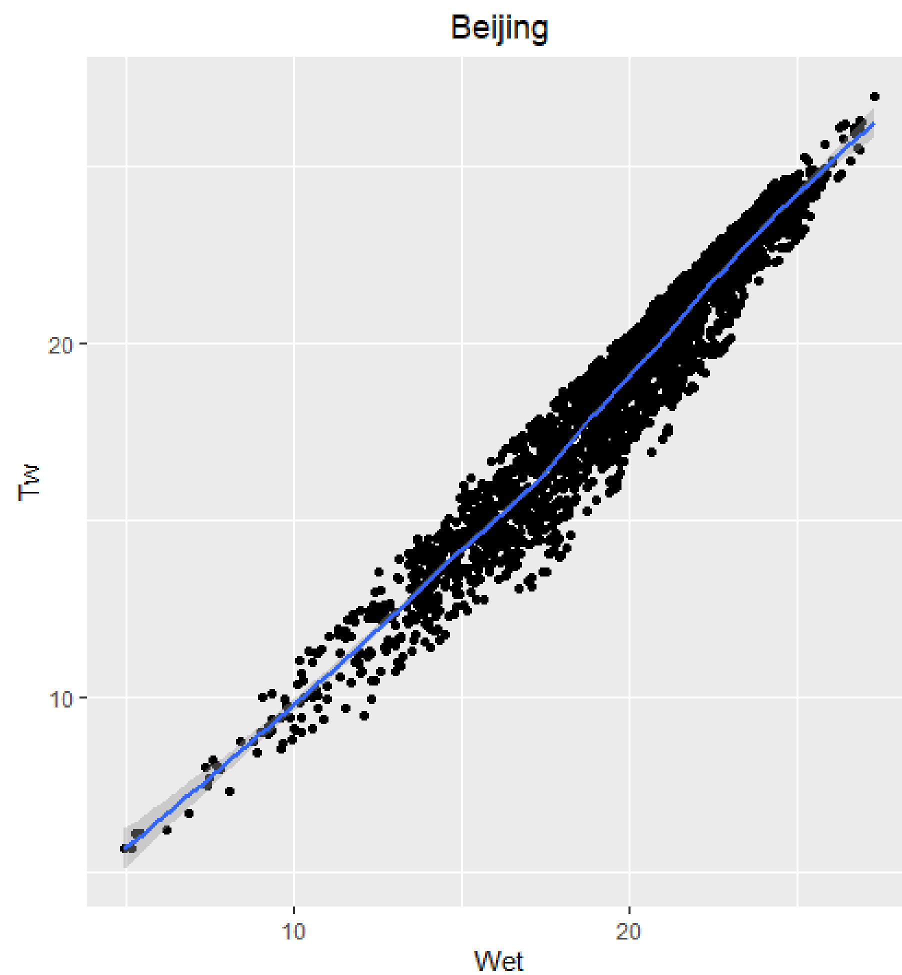
Feasibility study of IEC water chillers using in typical cities

- Beijing, China, outlet water temperature in 2020 summer
- The outlet cold water temperature is higher than 20℃ for about 50% hours
- Beijing is not suitable to use IEC water chillers as the cooling source

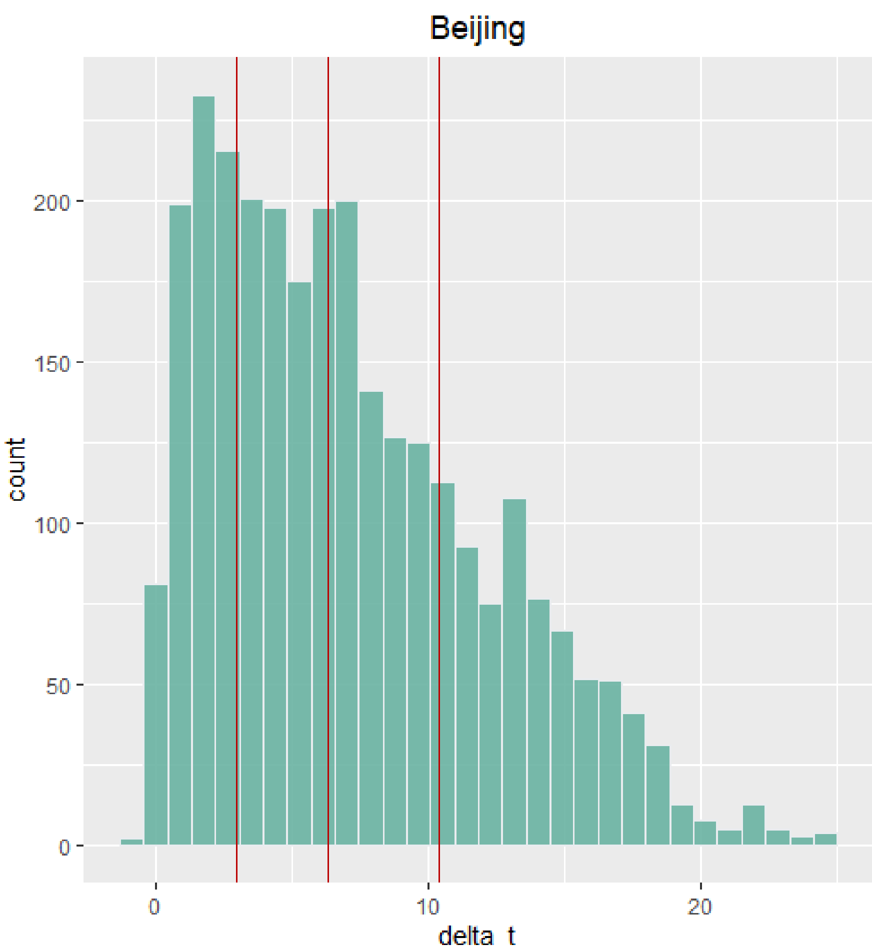




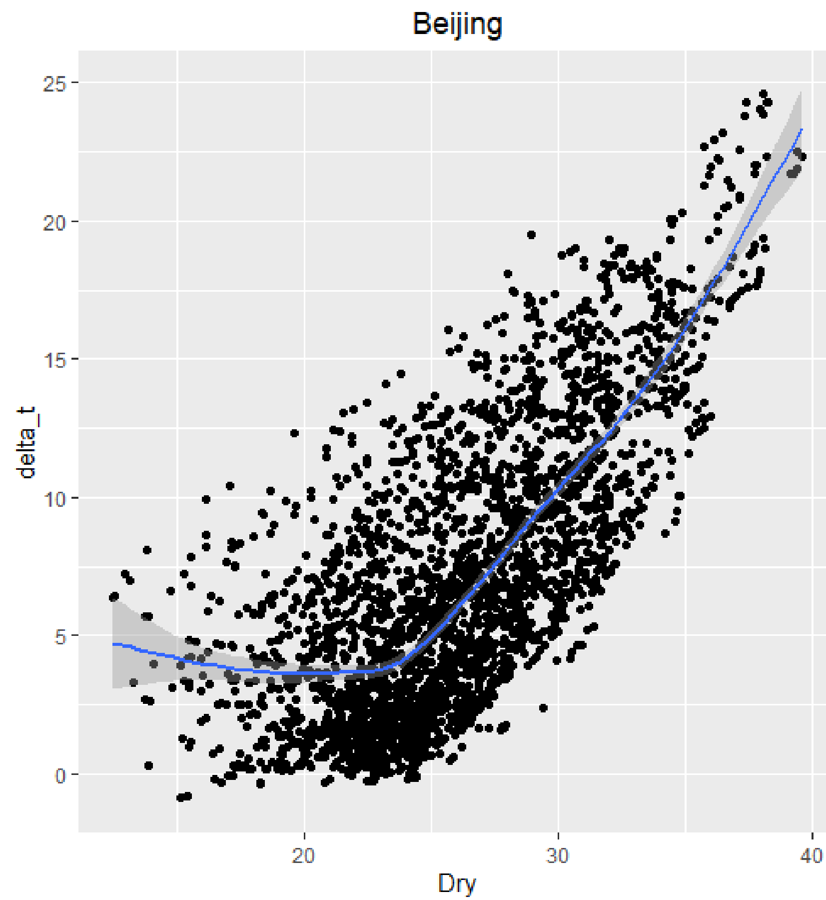
for HVAC professi Output cold water temperature

Feasibility study of IEC water chillers using in typical cities

- Beijing, China, 2020 summer
- The temperature difference between outdoor dry bulb temperature and output cold water temperature is higher than 7℃ for 50% hours, the higher the outdoor dry bulb temperature , the higher the temperature difference.
- IEC processes could be used for pre-cooling under Beijing climates.

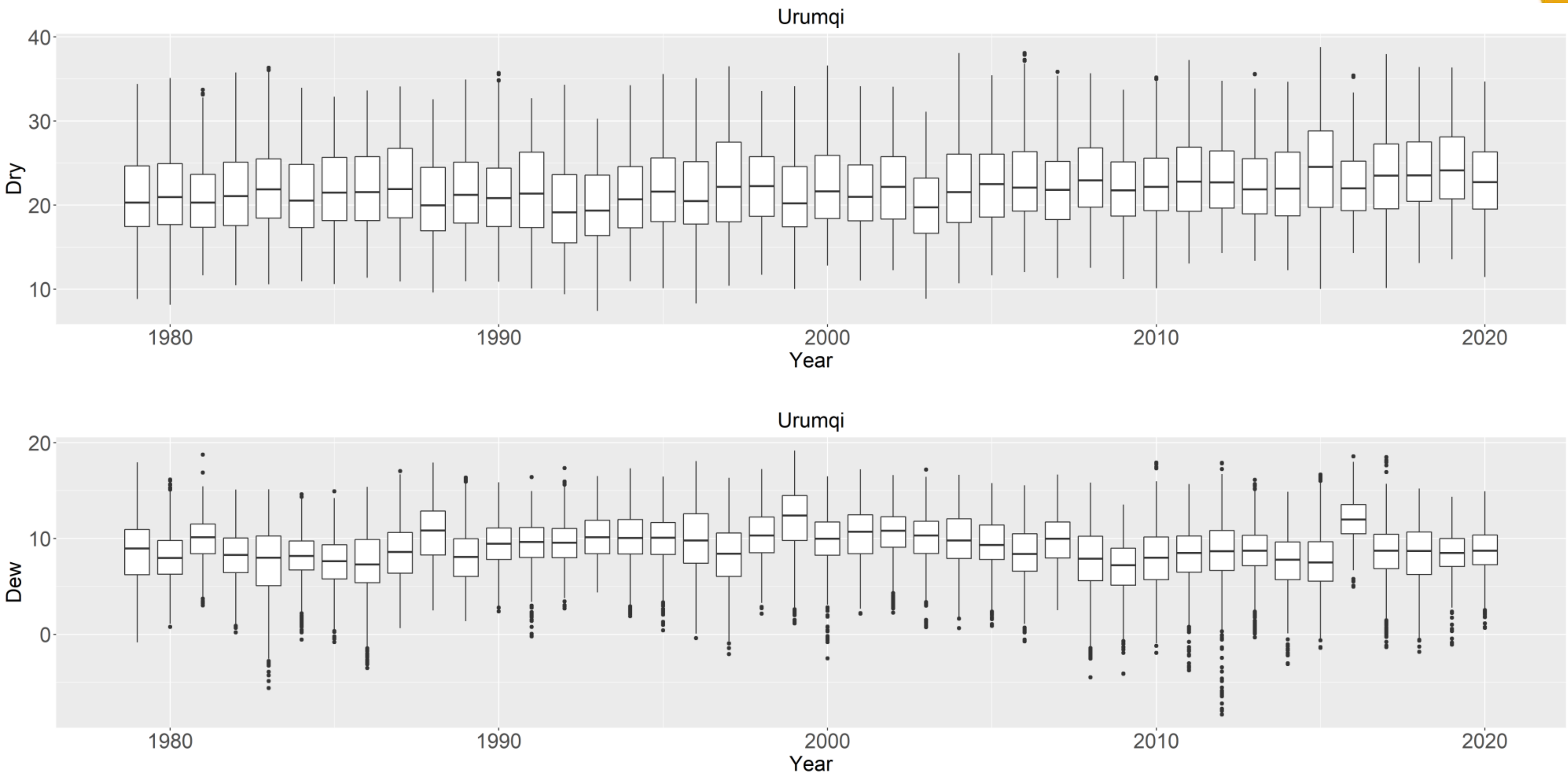


Temperature difference between outdoor air temperature and output cold water temperature



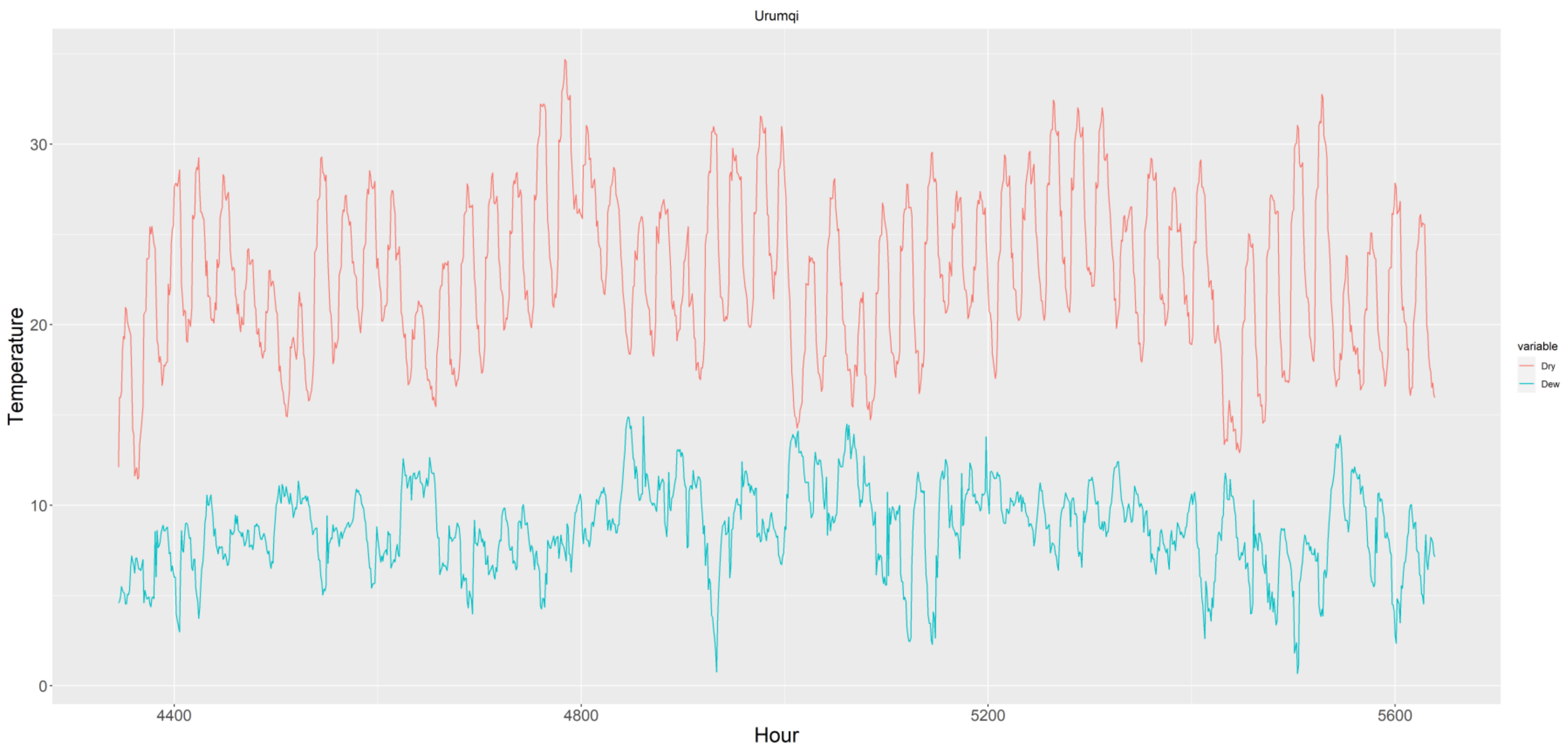
Feasibility study of IEC water chillers using in typical cities

- Urumqi, China, average outdoor conditions in summer



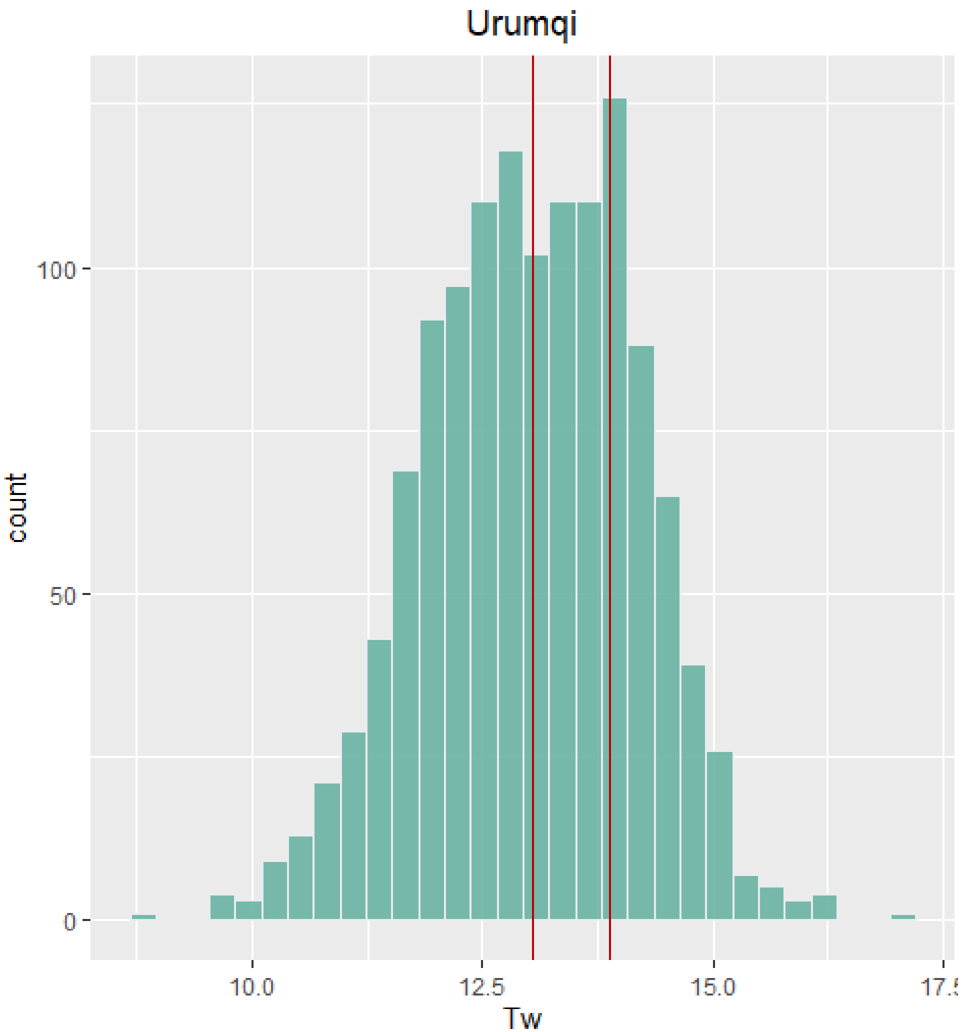
Feasibility study of IEC water chillers using in typical cities

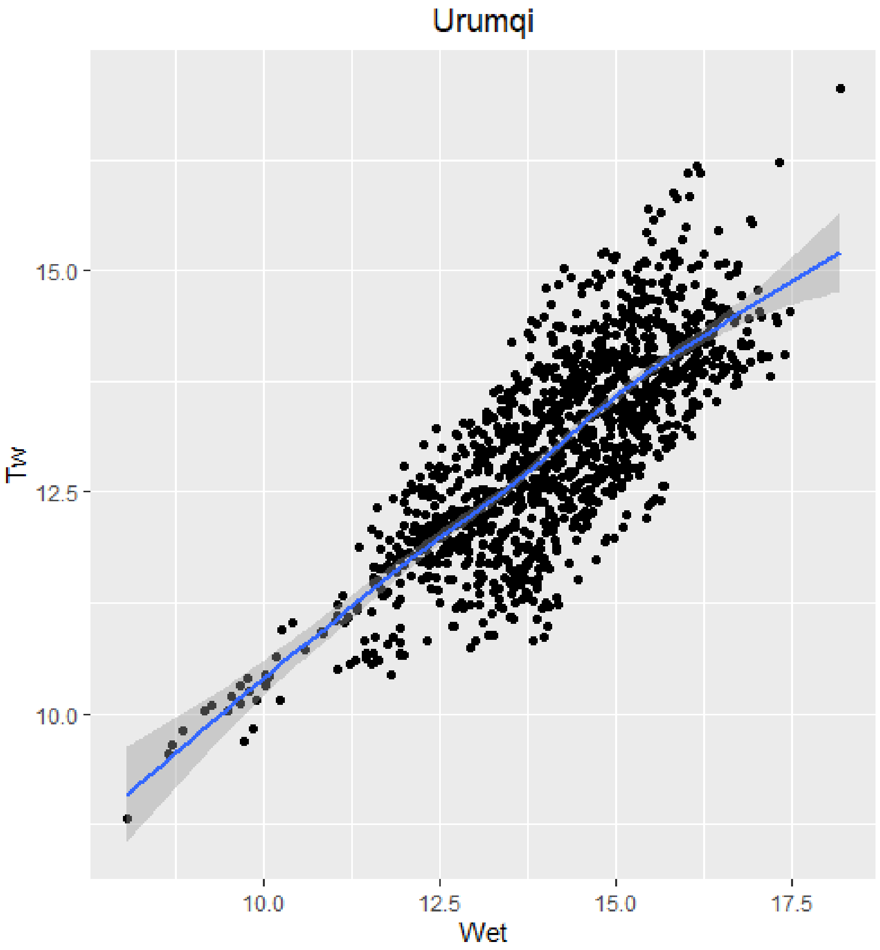
- Urumqi, China, outdoor air conditions in 2020 summer



Feasibility study of IEC water chillers using in typical cities

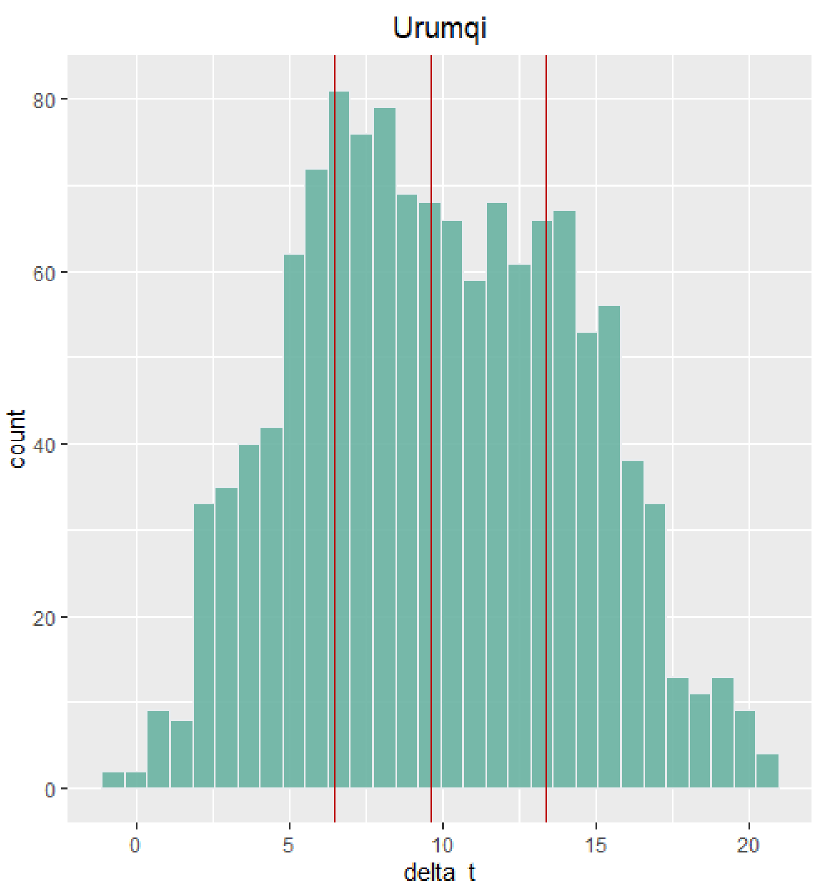
- Urumqi, China, average outdoor conditions in summer
- The outlet cold water temperature is lower than 18℃ for all the summer.
- Urumqi is quite suitable to use IEC water chillers as the cooling source

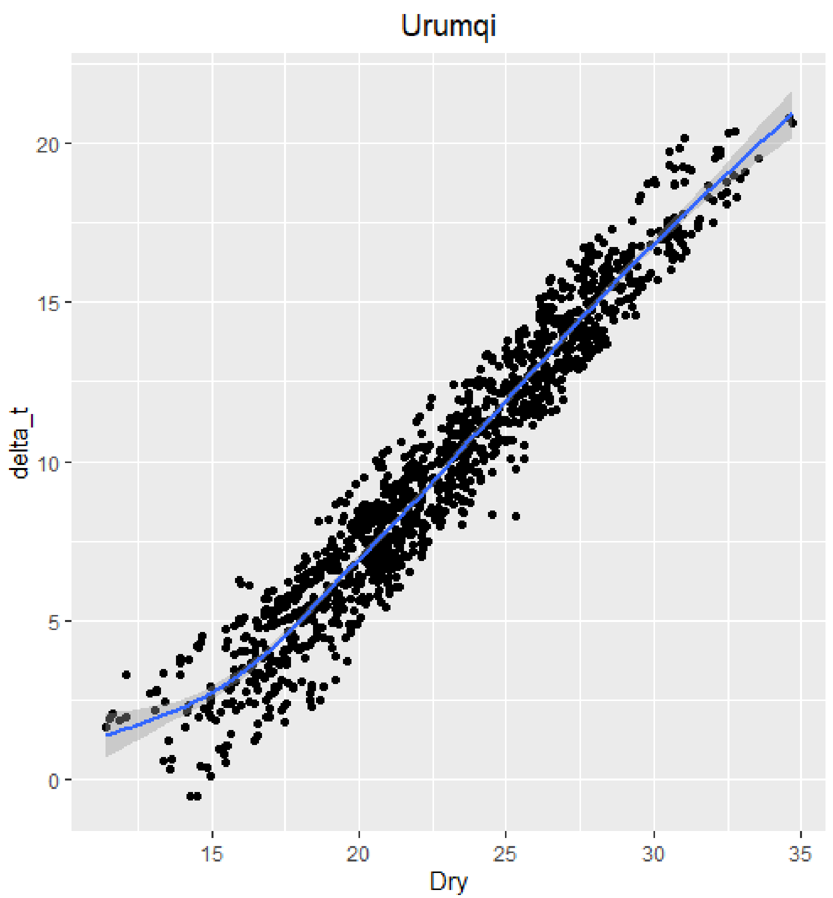




Feasibility study of IEC water chillers using in typical cities

- Urumqi, China, 2020 summer
- The temperature difference between outdoor dry bulb temperature and output cold water temperature is higher than 5℃ for about 75% hours, the higher the outdoor dry bulb temperature , the higher the temperature difference.
- IEC processes could be used for well for Urumqi climate, and the cooling capacity could fit with heat loads.





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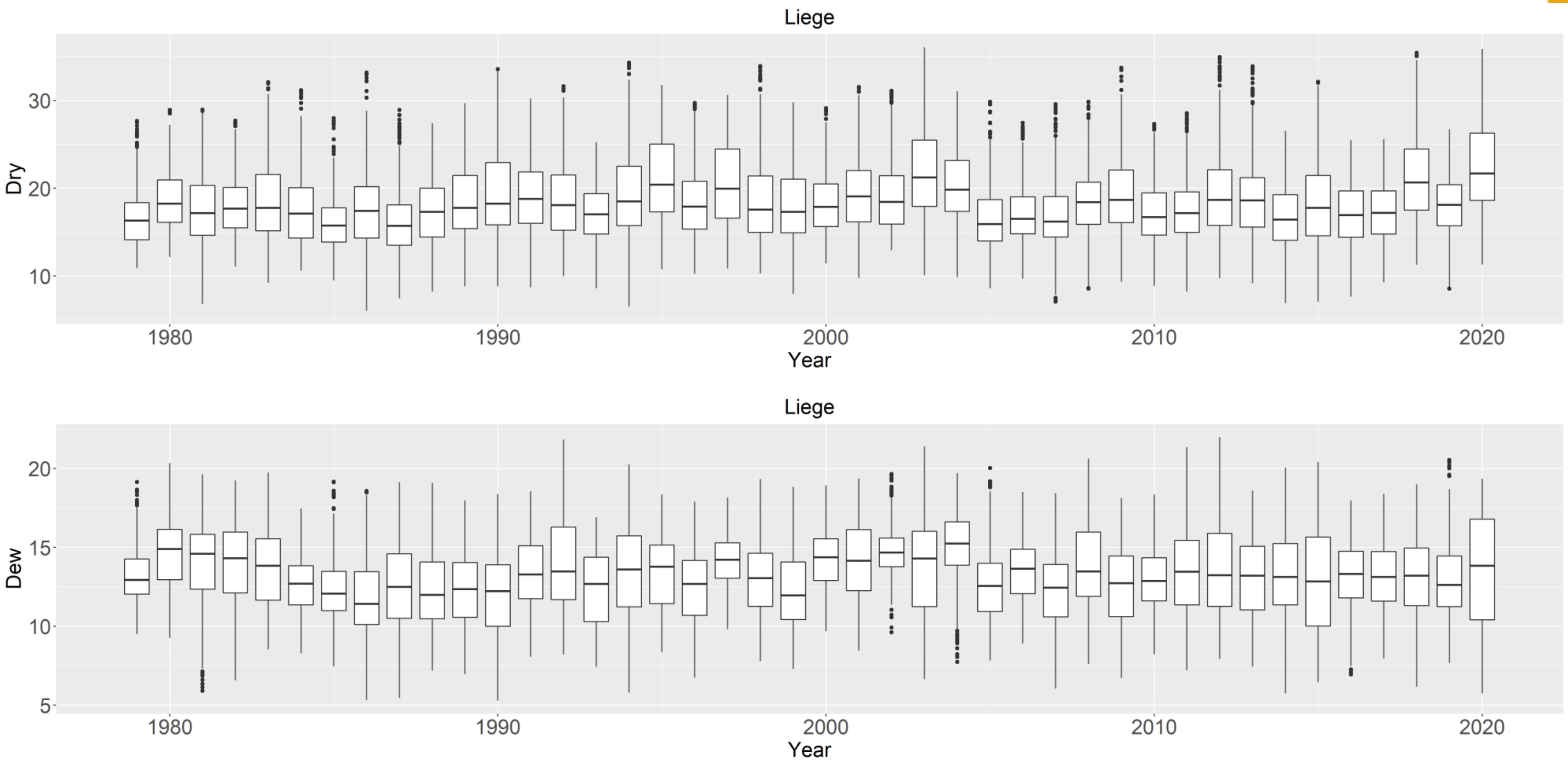
Temperature difference between outdoor air temperature and output cold water temperature

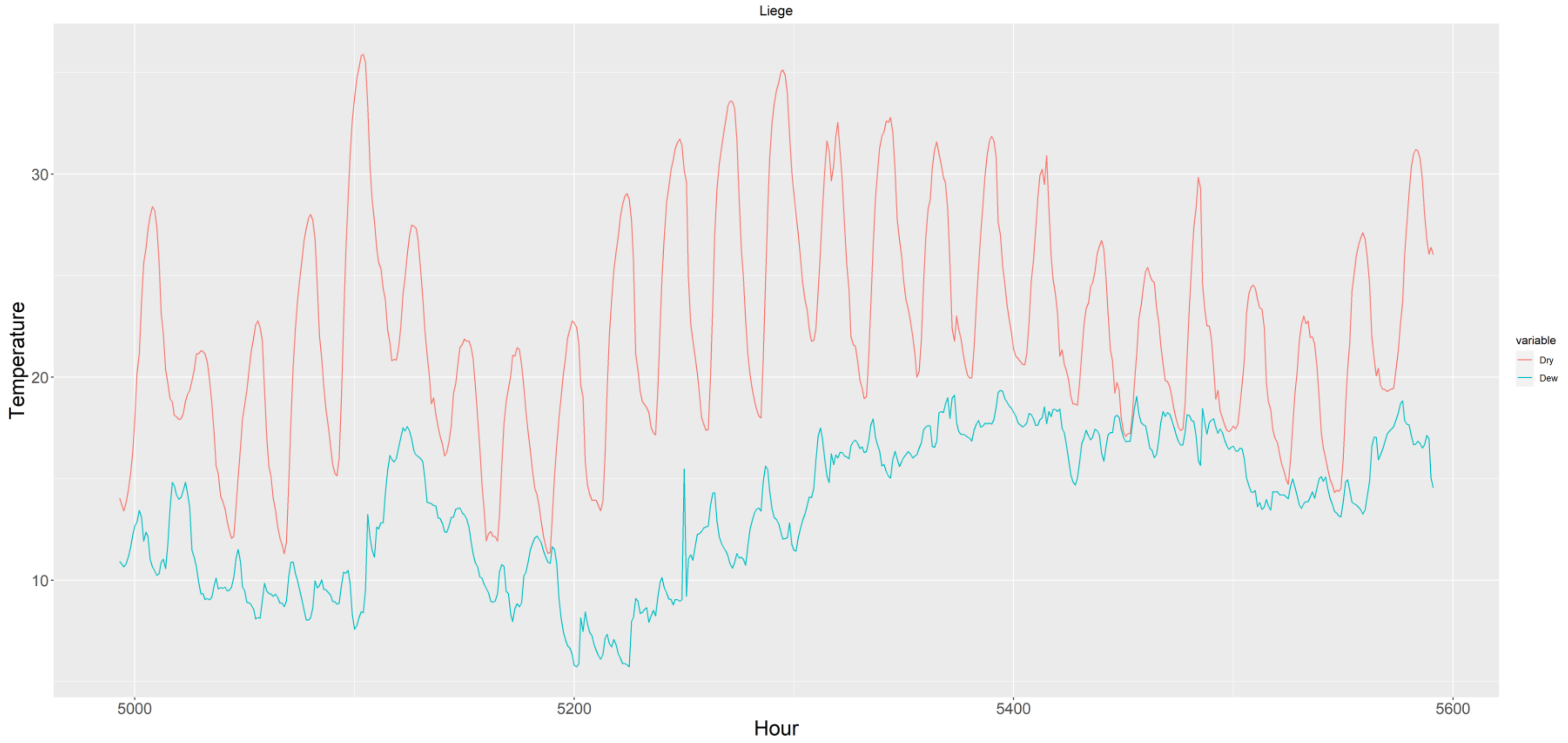
Feasibility study of IEC water chillers using in typical cities

- Liege, Belgium, average outdoor conditions in summer



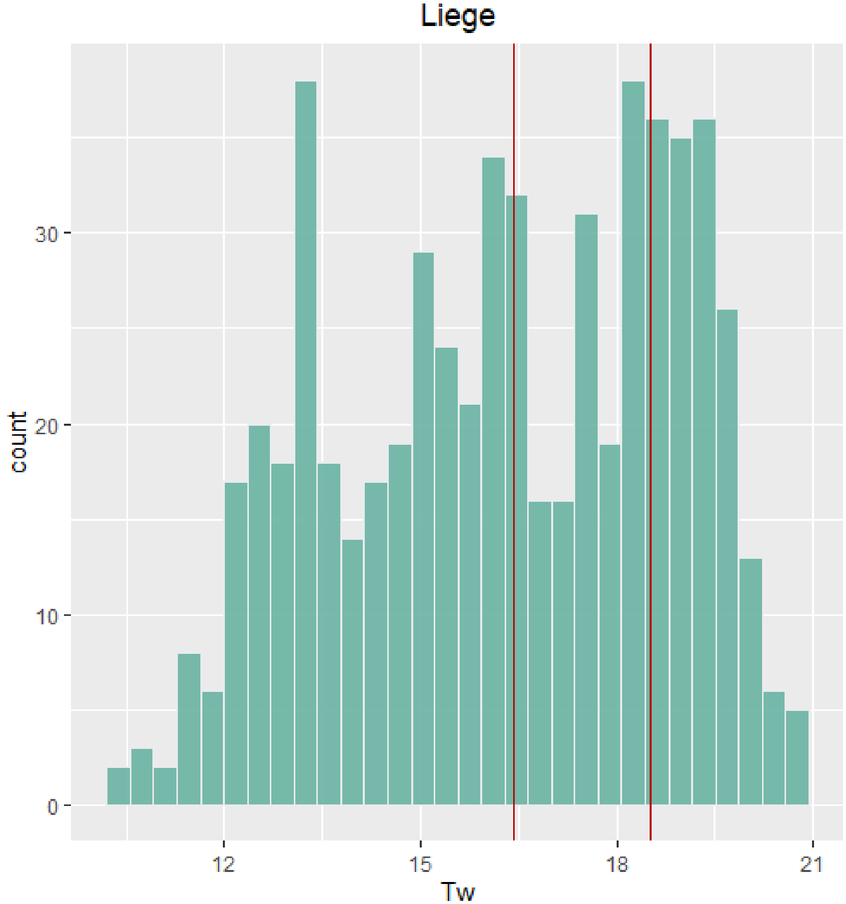
Feasibility study of IEC water chillers using in typical cities

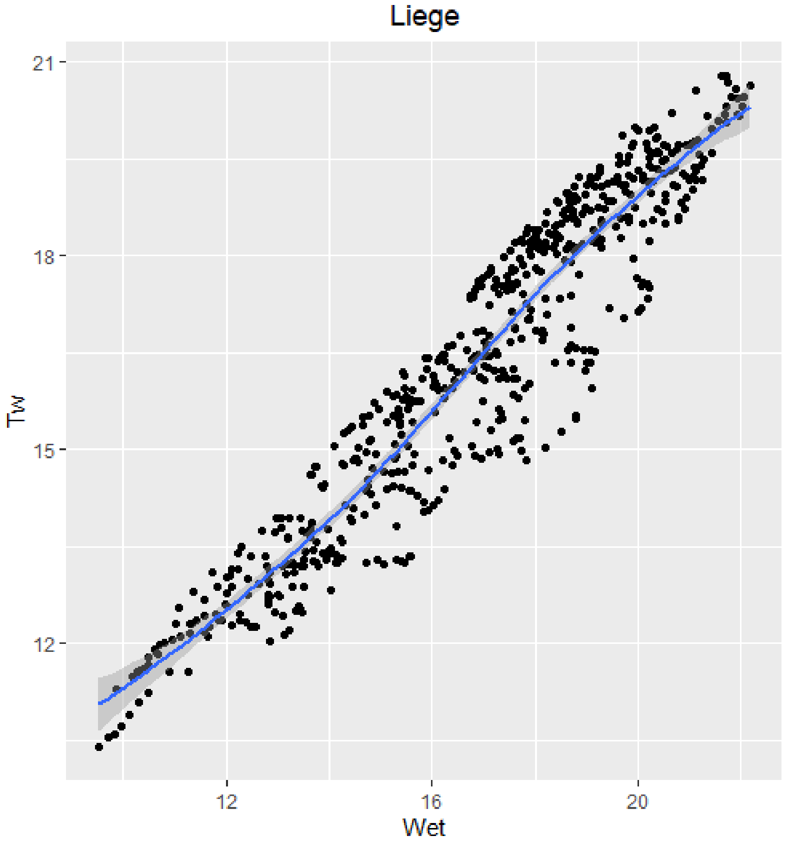
- Liege, Belgium, outdoor air conditions in 2020 summer



Feasibility study of IEC water chillers using in typical cities

- Liege, Belgium, in 2020 summer
- The outlet cold water temperature is lower than 18℃ for about 75% hours in the summer.
- Liege is suitable to use IEC water chillers as the cooling source.





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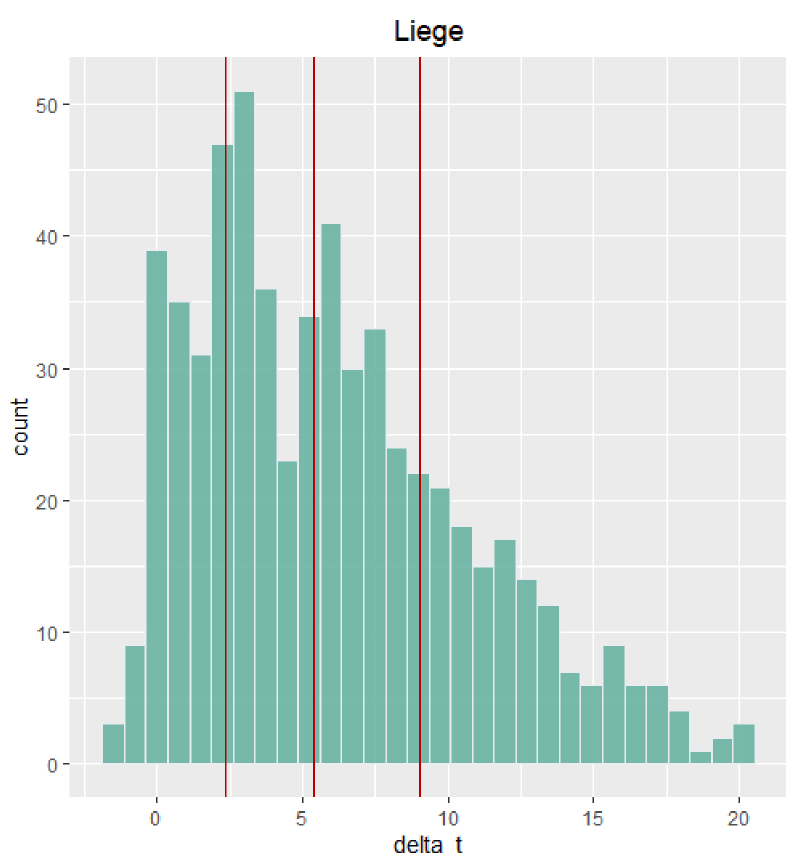
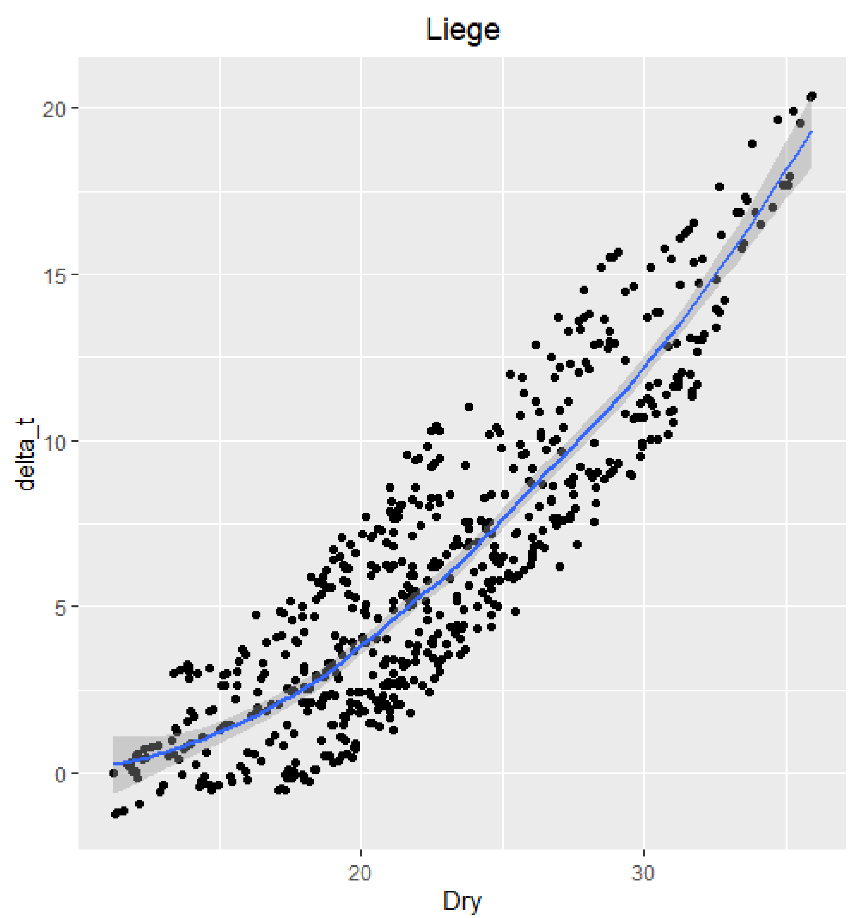
Feasibility study of IEC water chillers using in typical cities

- Liege, Belgium, 2020 summer
- The temperature difference between outdoor dry bulb temperature and output cold water temperature is higher than 10℃ for about 75% hours, the higher the outdoor dry bulb temperature , the higher the temperature difference.
- IEC processes could be used for well for Liege climate, and the cooling capacity could fit with heat loads.





Temperature difference between outdoor air temperature and output cold water temperature

Conclusions

- Through internal losses analysis, matching evaporative cooling process is identified, including parameter matching, flow pattern matching and flow rate matching.
- The indirect evaporative water chiller process is designed to realize matching and near reversible process, to produce cold water to inlet dewpoint temperature.
- Cooling performance, water consumption performance and electricity consumption are analyzed for indirect evaporative water chiller. Different IEC systems and different IEC processes are compared preliminarily.
- It is suitable to use IEC systems in dry climate with relative humidity low enough. where the relative humidity is higher than 65~70%, IEC technologies are not suitable as the performance is near that of DEC technologies.
- There already exist various projects of IEC technologies, whereas both fundamental and practical aspects remain to be studied through international collaboration.

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Thank you very much for your attention!

xiexiaoyun@tsinghua.edu.cn

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