Reducing cooling energy by system innovation

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Where is the energy lost through cooling?

- **Indoor** → chilled water → chiller → cooling water
  → cooling tower → outdoor
Where is the energy lost through cooling?

- The real demand for space cooling is just raising the heat Q for 3K from 25°C indoor to 28 °C outdoor, **the required work is 3Q [WK]**

- However the chiller does lift up the heat Q from 5 °C at the evaporator to 40 °C at the condenser, **the actual work is 35Q [WK]**, as many as 11 times!

- The additional **32Q have been paid for completing the heat transfer process** as well as heat flux mixed with different temperature during the heat transportation process from indoor to outdoor

- **The other reason is that dehumidification required.** To make moisture condensation, low temperature below dew point as the cooling source is needed
An Innovation of space cooling system

- **Separate humidity control from temperature control: THIC**
  - An independent air system added to remove latent heat for humidity control
  - Temperature can then be controlled by a high temperature cooling source (e.g., 15°C to 20°C) to remove sensible heat only
  - As sensible heat normally takes more than 70% of the total heat load, high efficiency cooling source can be used to remove sensible heat
    - Underground water or underground heat exchanger if ground temperature is below 15°C
    - Evaporate cooling can also provide cooling source if the dew point outdoor is below 15°C
    - COP for compression chiller can be achieved at 9 ~ 10 comparing with 5~6 at normal state

- **Reduce the temperature difference between indoor space and cooling source so to raise required cooling source temperatures as high as possible**

- **Reduce the power of fans and pumps by improvement of the heat delivering system**
An Innovation of space cooling system

- Separate humidity control from temperature control (THIC)
  - **Humidity control** as well as indoor air quality: **Dried outdoor air**
  - **Temperature control**: High temperature cooling source (or low temperature heating source in winter)

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### Operating principle of the THIC air-conditioning system

**Air-conditioning devices**
- Outdoor air processor
- Summer: Cooling source
  - Winter: Heat resource
- Radiant panel
- Dry FCU

**Terminal**
- Displacement vent
- Personalized vent.
- Control indoor humidity and CO₂
- Radiant panel
- Dry FCU
- Control indoor temperature

**Indoor environment**

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Temperature and Humidity independent Control (THIC) of Air-conditioning System. Berlin: Springer Press, 2014
Sensible heat removal for Temp. control

- In more than 40% of cooling applications in the world, the outdoor dew point is below 15°C. Moisture can be removed by air exchange with outdoor. **Space cooling is just to remove sensible heat.**

- To raise the cooling source temperature for high efficiency cooling, the key approach is to reduce the $\Delta t$ during heat delivering process:
  - Avoid the mixing loss of heat collection process at indoor terminals
  - Avoid $\Delta t$ loss of heat exchange process
  - Avoid the mixing loss of heat fluxes with different temperature
Terminal handling process

- Task: collecting heat and moisture from sources

Avoid mixing loss of heat collection process at indoor terminals!
Terminal handling process

- **Heat sources with different temperatures**

  - Heat sources’ temp. varying in the range of 26~40°C, or even higher
  - Significant mixing loss from heat sources to indoor air
Direct solar radiation

- Inner surface (Ts)
- Indoor air
- Supply air
- Chilled water
- Floor surface

Temperature / °C

Heat flux W/m²
> Simplify heat transfer process from heat sources to chilled water

Heat sources $\rightarrow$ Radiant floor surface $\rightarrow$ Chilled water

Heat sources $\rightarrow$ Indoor air $\rightarrow$ Supply air $\rightarrow$ Chilled water
Terminal handling process

> Reducing indoor mixing loss

> Decrease temperature gradient in space $\nabla T$

> Avoid fluid mixture of high temperature with low temperature
Terminal handling process

Jet ventilation

Jet supply air

~20m

~5m

Radiant floor

Displacement supply air

~2m

Radiant floor

Jet supply air

~20m

Indoor air

Supply air

Chilled water

Entransy Dissipation

Convective

Mixture

Entransy Dissipation

Entransy Dissipation

Heat flux W/m²

Temperature °C

0 20 40 60 80 100 120 140 160

0 5 10 15 20 25 30 35

Radiant floor

Displacement ventilation

Entransy Dissipation

Convective

Mixture

Conductive

Entransy Dissipation

Heat flux W/m²

Temperature °C

0 20 40 60 80 100 120 140 160

0 5 10 15 20 25 30 35
Terminal handling process

Entransy dissipation comparison

> Total entransy dissipation of System II (2411 (W·ºC)/m²)) is less than that of System I (3413 (W·ºC)/m²))
> Reduced entransy dissipation (1002 (W·ºC)/m²)) by system II equals to rising 6.3ºC of chilled water temperature.
Terminals with low mixing loss

- Radiant panels, radiant floor, TABs

- Radiant Panel
  - Ceiling height: 2.8m
  - Measuring Point: 1.5m above floor

- Embedded radiant systems: a) Floor, b) Ceiling, c) Wall, d) TABS
Application

- Terminal 3 of Xi’an airport
  - Area: 258,000m², with a maximum height of 36.5m
  - Coming into service since May 2012
- The first terminal adopting radiant cooling/heating in China
  - Radiant cooling, displacement ventilation, liquid desiccant …
AC system (summer)

- **Large space area**
  - Stratified air conditioning in summer

![Diagram showing AC system in summer](image)

- Radiant floor with high temp water
- Dry air
- Conditioned temp., low hum. zone
- Displacement ventilation
- Natural ventilation zone
- Entrance
- Infiltration

Approximately 20 m
Terminal handling process

Measured temperatures
### Radiant floor for cooling (without solar)

<table>
<thead>
<tr>
<th>Time</th>
<th>Temperature (°C)</th>
<th>Cooling capacity (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10:00</td>
<td>18</td>
<td>20~40</td>
</tr>
<tr>
<td>11:00</td>
<td>19</td>
<td>20~40</td>
</tr>
<tr>
<td>12:00</td>
<td>20</td>
<td>20~40</td>
</tr>
<tr>
<td>13:00</td>
<td>21</td>
<td>20~40</td>
</tr>
<tr>
<td>14:00</td>
<td>22</td>
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</tr>
<tr>
<td>15:00</td>
<td>23</td>
<td>20~40</td>
</tr>
<tr>
<td>16:00</td>
<td>24</td>
<td>20~40</td>
</tr>
</tbody>
</table>

**Temperatures**

**Cooling capacity**

*(20~40W/m²)*
Application

- Radiant floor for cooling (with solar)
  - Solar radiation on floor: High intensity, transient process

Cooling capacity could be higher than 100W/m² with direct solar radiation
Application

- Power consumption

Significant energy conservation benefits
Application

- Radiant terminal in a solar house (Denmark)
**Application**

- **Radiant terminal in a solar house (Denmark)**

Operative temperature and external air temperature during the cooling season

Floor cooling

Cooling capacity
Avoid Δt loss of heat exchange process

- Direct connection of the cooling source with indoor terminals
- Enlarge the heat transfer ability and adjust the flow rates at both sides so to ensure the Δt uniformed along the heat exchange process

Unmatched flow rates
Avoid $\Delta t$ loss of heat exchange process

- 4~5 K temperature difference for water circulation
- On-off control for each indoor terminal (radiative) to obtain near linear control performance
- Careful design of the water piping system to avoid large pump power consumed
  - Remove most of control valves and other resistance device in water loops except on-off control valve
  - Pressure drop: 10~15 m H$_2$O for total water loop circulation
Case study

- Evaporative cooling as cooling source
  - Outlet water temperature 15~19°C to remove sensible heat

- Key parts: countercurrent air cooler/packing tower
- Design idea: matched flow rates and parameters
Case study

- Evaporative cooling as cooling source

- Installed in Shihezi Kai Rui Building, now four years well-running.

- Shihezi outdoor design air state: dry bulb 32.8°C, wet bulb 21.5 °C.

- Designed water out temperature 18.5 °C, cooling Energy output 120kW.
Case study

**Evaporative cooling as cooling source**

- Out water Temperature **lower than inlet Wet Bulb Temperature**.
- Tested **COP** (sensible heat removed/power of fan and pump) **higher than 10**.
Case study

Evaporative cooling as cooling source

Applications in the dry region (Xinjiang province, China)

Shihezi Kai Rui Building
Aksu People’s Hospital
Xinjiang Chinese Medicine Hospital
Xinjiang Medical University Hospital
Xinjiang air force hospital
Office building of Xinjiang medicine hospital
Changji medicine hospital
Xinjiang international exhibition center
Suitable region for evaporative cooling

- **Climate condition:** dew point $\leq 15^\circ C$

- **System requirement:**
  - Low $\Delta t$ loss terminals with on-off control
  - Large water circulation with minimal pressure drop

Division:
Outdoor Humidity Ratio: 12g/kg

West China

West U.S.
Suitable region for evaporative cooling

- Climate condition: dew point $\leq 15^\circ C$

North Europe

Outdoor Humidity Ratio (g/kg)
Efficient dehumidification process

For moist region: humidity control is part of the task in space cooling

- Weak point of dehumidification by condensation:
  - Require the cooling source below dew point
  - Reheat, or mix with higher temperature environment

New approaches for dehumidification are required!
Efficient dehumidification process

New approaches for dehumidification

- Liquid desiccant dehumidification

- Multi-stage process for dehumidification, matched parameters
Efficient dehumidification process

- New approaches for dehumidification
  - Liquid desiccant dehumidification

- Close to the iso-relative humidity line instead of isenthalpic line
Efficient dehumidification process

- New approaches for dehumidification
  - Liquid desiccant dehumidification

<table>
<thead>
<tr>
<th></th>
<th>Cooling</th>
<th>Deep Dehumidify</th>
<th>Total Heat Recovery</th>
<th>Humidify</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh air t (°C)</td>
<td>36.0</td>
<td>22.8</td>
<td>22.8</td>
<td>35.9</td>
</tr>
<tr>
<td>Fresh air d (g/kg)</td>
<td>24.6</td>
<td>8.6</td>
<td>8.6</td>
<td>26.7</td>
</tr>
<tr>
<td>Supply air t (°C)</td>
<td>17.3</td>
<td>16.1</td>
<td>11.9</td>
<td>30.4</td>
</tr>
<tr>
<td>Supply air d (g/kg)</td>
<td>8.6</td>
<td>5.1</td>
<td>3.4</td>
<td>19.5</td>
</tr>
<tr>
<td>Return air t (°C)</td>
<td>26.0</td>
<td>33.2</td>
<td>26.3</td>
<td>26.1</td>
</tr>
<tr>
<td>Return air d (g/kg)</td>
<td>12.2</td>
<td>18.3</td>
<td>16.3</td>
<td>12.1</td>
</tr>
<tr>
<td>Exhaust air t (°C)</td>
<td>39.1</td>
<td>43.9</td>
<td>42.2</td>
<td>32.6</td>
</tr>
<tr>
<td>Exhaust air d (g/kg)</td>
<td>37.3</td>
<td>23.4</td>
<td>24.1</td>
<td>20.3</td>
</tr>
<tr>
<td>COP</td>
<td>5.00</td>
<td>2.32</td>
<td>1.74</td>
<td>62.5%</td>
</tr>
</tbody>
</table>
Efficient dehumidification process

- **New approaches for dehumidification**
  - Solid desiccant dehumidification *(DESICA, Japan)*

- Heat pump utilized for internal cooling in dehumidification
Efficient dehumidification process

New approaches for dehumidification
- Solid desiccant dehumidification *(DESICA, Japan)*

![Diagram of dehumidification process](image)

- Close to the iso-relative humidity line instead of isenthalpic line
- \(\text{COP} \) is as high as 4.0
Application——Liquid desiccant

- Temperature and Humidity Independent control system
## Application — Liquid desiccant

<table>
<thead>
<tr>
<th></th>
<th>Outdoor air process</th>
<th>Chilled water process</th>
<th>Chilled water pump</th>
<th>Cooling water pump</th>
<th>Cooling tower</th>
<th>Fan Coil Unit</th>
<th>Entire system</th>
</tr>
</thead>
<tbody>
<tr>
<td>OAHU</td>
<td>Fan</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooling capacity /kW</td>
<td>773.0</td>
<td>446.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1219.1</td>
</tr>
<tr>
<td>Energy consump /kW</td>
<td>166.9</td>
<td>52.5</td>
<td>30.6</td>
<td>14.6</td>
<td>3.7</td>
<td>19.4</td>
<td>307.7</td>
</tr>
<tr>
<td>COP</td>
<td>4.3</td>
<td></td>
<td></td>
<td>3.7</td>
<td></td>
<td></td>
<td>4.0</td>
</tr>
</tbody>
</table>

(OAHU = 4.6)

(Chiller = 8.5)
Annual power consumption: 32kWh/(m² AC area)
Common building in Shenzhen: ~50kWh/(m² AC area)
Energy saving: ~30%
Application——DESICA

Office building in Japan

DESICA for humidity control and VRF for temp. control
Application——DESICA

Office building in Japan

DESICA for humidity control and VRF for temp. control
Application—DESICA

DESICA for humidity control and VRF for temp. control

- Set temperature is 28°C
  - Conventional System: -46.5%
  - THIC System: -47.4%

- Set temperature is 26°C
  - Conventional System: -46.5%
  - THIC System: -46.5%

Graph showing average daily energy consumption for different systems and set temperatures.
THIC applications in China:

Over 10 million m² buildings since 2006

Dry area:
Indirect evap. cooling

Wet area:
Dehumidification solution
How much energy can be saved?

- **Office building in dry climate**
  - Conventional system for cooling: electricity used 50 kWh/m²,
    - Total cooling: 100 kWh/m², COP=2, fans: 17kWh/m², pumps: 11kWh/m², chiller:22kWh/m²
  - Evaporate cooling with the innovative system: electricity used 23kWh/m², 54% saved
    - Total cooling 100 kWh/m², COP=5, fans:8kWh/m², pumps: 15kWh/m²

- **Office building in moist region**
  - Conventional HVAC system for cooling: electricity used 65kWh/m²
    - Total cooling:130 kWh/m², COP=2, fans:22kWh/m², pumps:14kWh/m², chiller:29kWh/m²
  - THIC system: electricity used 44kWh/m², 32% saved
    - Total cooling:130kWh/m², dehumidifier with fan: 14kWh/m², pumps:15kWh/m², chiller:15kWh/m²
    - Latent heat:35kWh/m², COPL=2.5, sensible heat:95kWh/m², COPs=3.2
Conclusion

- Huge potential saving in space cooling technology!

- **Dry regions, ~40% of current cooling applications**
  - Direct/indirect evaporative cooling instead of mechanical chillers
  - System should be well designed both for indoor terminal and heat delivering to adapt “high temperature cooling”
  - More than 50% energy can be saved!

- **Moist regions: east China and US, Japan, south India**
  - Humidity should be treated independently with temperature
  - Desiccant humidity control techniques should be applied for dehumidification
  - Sensible heat should be removed with high temperature cooling source
  - About 30% saving can be achieved!
IEA EBC Annex 59

High Temperature Cooling & Low Temperature Heating In Buildings (2012-2016)
This presentation is the summary of EBC Annex 59:
High temperature cooling & low temperature heating in buildings
THANKS

For more information:
jiangyi@mail.tsinghua.edu.cn
Reducing $\Delta En$ in HV&AC system

2. Coupled Temp. & Humid. control

- $\sim7^\circ$C chilled water is required for cooling & dehumidification

**Conventional system**

**THIC system (for Temp. control)**
Adopting other approaches for Humid. control
Application in buildings——Data center

Conventional system

- Cold aisle
- Hot aisle
- Plenum
- Supply air
- Return air
- CRAC units

Racks

- Rack
- HEX

Air flow

- $T_{in}$
- $T_{out}$
- $T_{supply}$
- $T_{return}$
- $T_{ex}$

Outdoor Environment

- $T_{coldsource}$

Temperature

- $Q$
- $T_{chip}$
- $T_{ex}$
- $T_{supply}$

Heat

- Entransy dissipation of rack cooling process
- Entransy dissipation of air mixing process
- Entransy dissipation of heat exchanging process
- Entransy dissipation of heat flow into outdoor environment

- $Q$
Application in buildings——Data center

Internal cooled new system

Rack temp distribution
Room temp : 23℃
<table>
<thead>
<tr>
<th></th>
<th>Compressor power kW</th>
<th>Fan power kW</th>
<th>Server power kW</th>
<th>EER</th>
<th>Indoor air temp ºC</th>
<th>Evaporative temp ºC</th>
<th>Supply/Return air temp ºC</th>
<th>Rack inlet/exhaust air temp ºC</th>
<th>Outdoor air dry/wet bulb temp ºC</th>
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<tbody>
<tr>
<td><strong>January 2nd</strong></td>
<td>16.8</td>
<td>4.5</td>
<td>58</td>
<td>2.7</td>
<td>23.5</td>
<td>8.7</td>
<td>14/24</td>
<td>24/33</td>
<td>6 / 0.2°C</td>
</tr>
<tr>
<td><strong>May 7th</strong></td>
<td>18.0</td>
<td>4.2</td>
<td>56</td>
<td>2.5</td>
<td>24.6</td>
<td>8.5</td>
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**Current distributed cooling**

<table>
<thead>
<tr>
<th></th>
<th>Cooling tower kW</th>
<th>Chiller 1 power kW</th>
<th>Chiller 2 power kW</th>
<th>Pump power kW</th>
<th>Rack fan kW</th>
<th>Server power kW</th>
<th>Indoor air temp ºC</th>
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<td>6.4</td>
<td>6.8</td>
<td>2</td>
<td>3.1</td>
<td>59</td>
<td>3.2</td>
<td>23.0</td>
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<td>23.2/23.8</td>
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*Former: rack exhaust T=indoor T +9ºC
Current: rack exhaust T≈indoor T*
### Former CRAC

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<th>Compressor power kW</th>
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**EER:** Increased from 2.6 to 5.7  
**PUE:** Decreased from 1.6 to 1.35