New Strategies for Sustainable Buildings in Extreme Environments

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Distinctive buildings in extreme environments

Extreme outdoor environment
• Very hot
• Dry or extreme humid
• Strong solar radiation

Demand for higher quality
• Health
• Thermal comfort
• Lower energy consumption

Change in Sustainable Strategies
How to design sustainable buildings in extreme environments?

① Designing high and effective envelopes

② Synergism with natural (extreme) environment

③ Equipment system with higher efficiency

④ Thermal adaptation and comfort improvement of human body
Traditional sustainable strategies for extreme climate

Shading, Natural ventilation, Atomization/fogger cooling…

Wind tower

Atomization/fogger cooling
Citizen Center, Haikou, China
Citizen Center, Haikou, China

Shading Analysis
遮阳分析

夏季太阳高度角：
47°（冬）-50°（夏）
日照时长：
10h56min（冬至）-13h21min（夏至）

冬季太阳方位角变化较大，
夏季太阳方位角变化较小。

在炎热的5-8月，北向，太阳主要在北偏
在冬季太阳高度角高，中午在30-50°之间。
在冬季太阳高度角低，中午在55-65°之间。

通风分析

夏季主导风：
南风10-15km/h
北风5-10km/h

冬季主导风：
东北风15-20km/h
Agricultural Expo Exhibition Hall, Chengdu, China

Shading + Natural ventilation, + Fogger cooling…
Apartments, Haikou south, China
1. Building envelope improvement — Shading and ventilation

- An adaptive shading and daylighting system—SVM (Shape-Variable Mashrabiya)
- Consisting of three identical opaque backscattering shields, and able to move relative to each other so as to switch between in the shading and lighting

Combines the advantages of building shading and lighting

- SVM is able to effectively block the solar radiation in the presence of direct sunlight, thus avoiding overheating of building spaces and minimizing glare issues. When direct radiation is absent, the SVM allows important skylight penetration while restoring some view to the outside.
- A high amount of direct sunlight is transformed into diffuse light providing more visual comfort to the users.

Images of the SVM: opened (left) and closed (right) configurations.
1. Building envelope improvement — Shading and ventilation

- Sun shading device integrated with solar energy collector and photovoltaic panel
- Using the characteristics of solar radiation and dry in extreme environments, building shading is combined with solar energy collection to control shading, while using solar energy and photovoltaic power generation.

Using PV panels as movable shading device in winter and summer

Involute shading collector elements and installation diagram
1. Building envelope improvement — Shading and ventilation

- Phase change materials assisted night purge ventilation
- This method uses the cool of the night to release the warmth stored in the thermal mass during the day.

**PCM+Night purge ventilation**

- the low mass and high energy storage capacity of PCMs augment the thermal inertia of buildings
- night ventilation removes the heat stored in the building during the day
1. Building envelope improvement — Shading and ventilation

- Demand controlled ventilation strategy with data-driven model and air balancing control
- The ventilation strategy consists of two steps: system model construction and air balancing control

**Based on data-driven model and air balancing control**

- Use data for training to optimize building ventilation performance
- The ventilation control strategy effectively solves the problem of over-ventilation and under-ventilation of the ventilation system, and achieves energy saving of fan power
1. Building envelope improvement — Radiative cooling

- Radiative cooling: Inspired by nature
- Applied in buildings: passive cooling, heat dissipation to outer space

Achieve passive cooling in daytime
- High solar reflectance
- Enhance the radiation and heat dissipation through the atmospheric window
1. Building envelope improvement — Radiative cooling

- Daytime radiative cooling: Great progress has been made in materials innovation

- **1st Study**
  - But only limited to nighttime radiative cooling

- **Catalanotti et al., Solar Energy 17, (1975)**
  - SiN, (70 nm)
  - Si (700 nm)
  - Al (150 nm)
  - Si substrate

  - Photonic radiative cooler
  - Non-vacuum

- **Chen et al., Nature Communications 7, (2016)**
  - Photonic radiative cooler
  - Vacuum

- **Zhai et al., Science 355, (2017)**
  - Polymer radiative cooler
  - Hybrid metamaterial

- **Kou et al., ACS Photonics 4, (2017)**
  - Polymer radiative cooler
  - Bilayer of SiO$_2$ and PDMS, backed by Ag reflector

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**Performance Enhanced**
1. Building envelope improvement — Radiative cooling

- Novel material: Polymer radiation material (University of Colorado)
- Infrared emissivity greater than 0.93
- When the material is backed with silver coating, the noon radiation cooling power of the material reaches 93W/m² under direct sunlight.
1. Building envelope improvement — Radiative cooling

- Polymer radiation material
  - Mass production has been carried out, and the material is flexible and can be wound
  - Mixed metamaterial film: width 300mm, thickness 50μm
  - Industrial production: 1 roll (5m long) / minute
1. Building envelope improvement — Radiative cooling

- The polymer radiation material has achieved mass production
- Applied in airport terminal
1. Building envelope improvement — Radiative cooling

- The polymer radiation: theoretic sustainability analysis
- In summer condition (building size 6.9*4.2*3.5m)
- Suitable for extremely hot environments

Outdoor air velocity 2m/s
- Clear sky and cloudless
- Cooling power > 42W/m²
2. Utilization of natural environment — Solar Energy

- Solar energy: Reliable renewable energy in extreme environments
- Photovoltaic Air conditioner: utilization of solar energy
- Flexible and efficient; Energy saving and low carbon
2. Utilization of natural environment — Solar Energy

- Photovoltaic Air conditioner: could achieve Net zero energy consumption and zero carbon (designed and manufactured by Gree)
- Won the Global Quality Innovation Award
2. Utilization of natural environment — Solar Energy

- Sustainable (Zero carbon) case: Photovoltaic Air conditioner

Phoenix (U.S.A)  
Hospital (Pakistan)  
Warehouse (Saudi Arabia)  
Factory  
Office building  
School
3. Higher efficient equipment and system — UEAC

- An **Ultra-Efficient Air Conditioner** for cooling: energy saving for extreme environments

**High performance systems and components**
- Dual evaporators and condensers
- Cascade-heat-transfer refrigeration cycle

**Natural energy utilization**
- Fresh air evaporative cooling and ventilation
- Evaporative cooling of unit

**Low carbon and renewable energy**
- Photovoltaic direct-drive technology
- Low GWP refrigerant R152a

**Ultra-Efficient Air Conditioner Integrated with Evaporative Cooling Fresh Air and Photovoltaic**

**Especially suitable for Tropical monsoon and Tropical savanna climate**
3. Higher efficient equipment and system — UEAC

- The Research & Development path

**Preliminary stage**
- 2018.11 Competition start
- 2019.6 Registration deadline
- 2019.8 Detailed Technical
- 2019.10 Announcement of Finalists

**Participant Engagement for final stage**
- 2019.10-2020.8 Prototype Development

**Final stage**
- 2021.4 Grand Award Ceremony
- 2021.2 SEER test
- 2020.12 Lab Testing
- 2020.10 Field Testing

**Sponsor:**
- GREE
- Tsinghua University
- M.R.I.
- Mission Innovation
3. Higher efficient equipment and system — UEAC

- Simulation results

- Annual total power consumption reduced to **585 kWh**
- Compressor energy consumption accounts for **79.8%**
- Fans energy consumption accounts for **20.0%**
3. Higher efficient equipment and system — UEAC

- 10-day lab test

- Typical 10-day lab-simulated year-round performance test
- Converted annual power consumption: 739 kWh
- Reduced annual power consumption: 84.3%
- Reduced carbon emissions: 85.7%
3. Higher efficient equipment and system — UEAC

- **Field test**

  - A field test in an actual south-facing residential apartment
  - The test period lasted 31 days, from October 1st to 31st
  - Independent ventilator operation hours accounted for **38.4%**
  - Electricity savings reached **89.8%**
3. Higher efficient equipment and system — **UEAC**

- **The Global Cooling Prize – Grand Winner**

April 30, 2021

Beijing National Convention Center

*Reported by CCTV News (China Central Television)*
3. Higher efficient equipment and system — THIC

- Temperature and Humidity Independent Control
- Eliminating sensible heat load and latent heat load independently
- Improving system COP by utilizing high temperature cold source

\[
E = \frac{COP_{\text{sys}(\sim7^\circ C)}}{COP_{\text{Deh}}}
\]

**Conventional**

Low temperature cold source

**THIC**

High temperature cold source

\[
E = \frac{COP_{\text{sys}(\sim16^\circ C)}}{COP_{\text{Deh}}} + \frac{COP_{\text{Deh}}}{COP_{\text{sys}(\sim16^\circ C)}}
\]

Improving COP_{sys}: >30%!
3. Higher efficient equipment and system — THIC

- Temperature and Humidity Independent Control
- Latent heat load: by liquid desiccant
- Sensible heat load: improving system efficiency by decreasing the demand for low temperature cold source

*Centrifugal water chiller (tested results)*

*COP increase >35%*
3. Higher efficient equipment and system — THIC

- **Temperature and Humidity Independent Control**
- Especially suitable for extreme environment

Dehumidification method
Indirect evaporative cooling

Natural cooling source
Mechanical chiller

**High temperature cooling source**
16~18°C water or refrigerant

**Air-supply terminal**

**Sensible terminal**

16~20°C, 8~9g/kg

Displacement ventilation; Personalized ventilation

Radiant panel
Dry fan coil
3. Higher efficient equipment and system — THIC

- **Temperature and Humidity Independent Control**
- Application: different climate regions and building types

THIC system applications:
- 20 million m² of buildings in recent 5 years

- Large space building
- Industrial building
- Office building
4. Thermal adaptation theory and application

- The Ceiling fans are widely used in many countries
  - Reduce indoor thermal stress & improved thermal comfort
  - Reduce energy consumption 30% by increasing indoor air velocity and setting temperature
  - Improve indoor air temperature stratification for tall space heated buildings
4. Thermal adaptation theory and application

- Human shows higher thermal comfort in under a natural draft condition
- The comfortable ambient temperature of naturally ventilated buildings is significantly higher than the design temperature of air conditioning
4. Thermal adaptation theory and application

- Collecting natural wind characteristics
- Establishing the frequency of natural wind

- Mechanical ventilation
- Sinusoidal ventilation
- Naturalistic ventilation
4. Thermal adaptation theory and application

- Developing mechanical ventilation fans: imitating natural wind
- Suitable for buildings in extreme environment
  - Reducing the set temperature of the air conditioning system
  - Reducing energy demand and carbon emissions
  - Improving the health and thermal comfort
Summary: design sustainable buildings in extreme environments with this 4 strategies

① Designing high and effective envelopes

② Synergism with natural (extreme) environment

③ Equipment system with higher efficiency

④ Thermal adaptation and comfort improvement of human body
Thanks for listening!