Passive Radiative Cooling Development for Use in Built Environment

Christopher Chao
Head & Chair Professor of Mechanical and Aerospace Engineering
The Hong Kong University of Science and Technology

Thermal comfort is currently well-controlled by HVAC, but this ACTIVE approach has high energy consumption. Any innovative and PASSIVE approach?
Passive Radiative Cooling

Radiative cooling is the process of heat removal from a sky-facing surface to the universe through radiation, cooling the surface below ambient temperature.

Funding:
- CRF (C6022-16GF): Study of Cooling Effect by Surface Treatment and its Application to Smart Green Buildings (~7M) → Led by CYH Chao (HKUST)
- ITSP (ITS/013/16): Development of a high-performance passive radiative cooler for buildings (~1.4M)

Working Principle of Passive Radiative Cooling

To achieve daytime cooling:
- High solar reflection;
- Eliminating heat via radiative emission through the atmospheric window.
**Working Principle of Photonic/Plasmonic/Polymer-based Passive Radiative Coolers**

**Photonic & Polymer-based Passive Radiative Coolers**

- **Two stage absorption**
  - e.g. SiO$_2$ + HfO$_2$ or SiO$_2$ + PDMS

**Infrared reflector**
- Metals: Ag or Au or Cu

**Photonic/Polymer Structure**
- Wavelength (µm)
- Total reflection (i.e. absorptance = 0)
- Strong absorptance (~1)

Size of particles < visible λ → Plasmonics phenomenon

Surface plasmon confined at metal-dielectric interfaces, a collective resonance oscillation of charges induced by light, can lead to extremely high local photon density of states (up to 10 – 1,000 times enhancement) at certain energy level, leading to much improved emissivity/absorptivity within these resonance bands in a small regime with minor influence on lights in other bands.

**Differences among Photonic, Plasmonic and Polymer-based Radiative Coolers**

<table>
<thead>
<tr>
<th></th>
<th>Photonic</th>
<th>Plasmonic</th>
<th>Polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanism</strong></td>
<td>Selective thermal emission executed by interatomic vibration of constituent atoms</td>
<td>Selective thermal emission executed by surface plasmon polaritons</td>
<td>Selective thermal emission executed by interatomic vibration of constituent atoms</td>
</tr>
<tr>
<td><strong>Materials</strong></td>
<td>SiO$_2$ + HfO$_2$/TiO$_2$/Si$_3$N$_4$</td>
<td>Al, Ge, Ag, SiN$_x$, Al$_2$O$_3$</td>
<td>PDMS + SiO$_2$ or PMP + SiO$_2$</td>
</tr>
</tbody>
</table>


Development of Passive Radiative Coolers

Daytime Radiative Cooling

- 3rd Study
- Has only limited to nighttime radiative cooling
- Catalano et al., Solar Energy 17 (1975)
- Photic cooling
- Non-vacuum
- Photic cooling
- Vacuum

Performance Enhanced


Multi-layer Photonic Passive Radiative Cooler

Tested under hot and humid climate (Hong Kong)

Multi-layer Photonic Passive Radiative Cooler – Work in Progress

Vacuum Design (Revised) Rooftop of the CYT building at the HKUST

Results:
Cooling Effects during the daytime, but poor in cloudy days

![Graph showing daytime clear sky with reduced temperature](image)

~8 °C reduction during the daytime operation

Research Challenge

Major Problem: Reduced cooling power under a humid climate (i.e. Hong Kong)

In a highly humid environment, transparency of the atmospheric window is lost → thermal emission within 8-13μm increases.

Can we block the 8-13μm thermal radiation from the water vapour in the atmosphere to the radiative cooler?

Proposed Solution: Asymmetric Electro-Magnetic Transmission (AEMT) Window

Reflecting incoming radiation of the 8-13 μm from the atmosphere

Permitting outgoing mid-infrared transmission emitted by the radiative cooler (8-13 μm)

Asymmetric transmission window

Radiative cooler

AEMT Window FDTD Simulation Results

50W/m² (+140% improvement)

Nighttime radiative cooling only (1975)

Daytime applicable (2014), but expensive

Daytime with low-cost cooler, but it is only successful under clear sky and low humid climate

Future direction: promising radiative coolers + asymmetric electro-magnetic transmission windows

Promising Radiative Cooler (1): Low Cost Multi-layer SiO$_2$-TiO$_2$ Photonic Radiative Coolers

<table>
<thead>
<tr>
<th>Low Cost Multi-layer Photonic Radiative Cooler</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Number of sub-layers:</strong> 8</td>
</tr>
<tr>
<td><strong>Sub-layer thickness:</strong> 500 nm SiO$_2$ + 500 nm TiO$_2$</td>
</tr>
<tr>
<td><strong>Total Thickness:</strong> 4 $\mu$m</td>
</tr>
<tr>
<td><strong>Backing reflector material:</strong> Ag</td>
</tr>
</tbody>
</table>

35% Cost Reduction
Advantages of plasmonics: Very strong selective absorption/emission in a small regime, so that the structure can be quite thin and simple, which can reduce the fabrication cost.

The plasmonic structure can work as scattering elements to couple and trap freely propagating incident photons in free space into the photon absorption regime. These combined effects can lead to much stronger photon absorption in a target spectral range.

Promising Radiative Cooler (3): Biomimetic Thermal Selective Passive Radiative Cooler (Polymer-based Cooler)

Saharan Silver Ant (*Cataglyphis Bombycina*)
- Inhabit Saharan Desert;
- Endures strong sunlight (i.e. high temperature);
- Forages during the hottest time of the day;
- Covered by the triangular prism shaped hair.

Thermoregulatory effect of the hair
- Enhanced reflectivity in visible & NIR
  - With Hair: reflects 67% of the solar radiation
  - Without Hair: only 41%
- Enhanced emissivity in MIR
  - Hair cover enhances by about 15%

FDTD Simulation Results of Biomimetic Passive Radiative Coolers

FDTD Simulation to optimize emissivity of biomimetic polymer-based radiative cooler

Parameters for optimization:
- Thickness of substrate
- Geometry (i.e. triangle, circular, flat plane, etc.)
- Size of geometrical structure
- No. of surface layers

Triangular structure shows a big difference from the other two geometrical structures

<table>
<thead>
<tr>
<th>Model</th>
<th>Configuration</th>
<th>Averaged Emissivity (6-13μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat plane (a=8μm)</td>
<td></td>
<td>0.875</td>
</tr>
<tr>
<td>Flat plane (a=11μm)</td>
<td></td>
<td>0.910</td>
</tr>
<tr>
<td>Single layer circular rod (a=8μm)</td>
<td></td>
<td>0.914</td>
</tr>
<tr>
<td>Single layer circular rod (a=11μm)</td>
<td></td>
<td>0.956</td>
</tr>
<tr>
<td>Single layer triangular prism (a=8μm)</td>
<td></td>
<td>0.959</td>
</tr>
<tr>
<td>Single layer triangular prism (a=11μm)</td>
<td></td>
<td>0.960</td>
</tr>
<tr>
<td>Double layer triangular prism (a=8μm)</td>
<td></td>
<td>0.967</td>
</tr>
<tr>
<td>Double layer triangular prism (a=11μm)</td>
<td></td>
<td>0.974</td>
</tr>
<tr>
<td>Complex model 1</td>
<td></td>
<td>0.923</td>
</tr>
<tr>
<td>Complex model 2</td>
<td></td>
<td>0.961</td>
</tr>
<tr>
<td>Complex model 3</td>
<td></td>
<td>0.972</td>
</tr>
</tbody>
</table>

Comparison among all Potential Passive Radiative Coolers

<table>
<thead>
<tr>
<th></th>
<th>Photonic</th>
<th>Plasmonic</th>
<th>Polymer with Rectangular Shape</th>
<th>Polymer with Triangular Shape (Biomimetic thermal selective radiative cooler)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance</td>
<td>Acceptable</td>
<td>Excellent</td>
<td>Good</td>
<td>Very Good</td>
</tr>
<tr>
<td>Manufacturing Difficulty</td>
<td>Medium</td>
<td>Medium</td>
<td>Easy</td>
<td>Easy</td>
</tr>
<tr>
<td>Material Cost</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Fabrication Cost</td>
<td>Highest</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
</tr>
</tbody>
</table>
Five Unknown Temperatures:
1. $T_r$: Air temp. inside the room
2. $T_{c,\text{air}}$: Cold air temp.
3. $T_{h,w}$: Hot water temp.
4. $T_{c,w}$: Cold water temp.
5. $T_{\text{p,rc}}$: Radiative cooler temp.