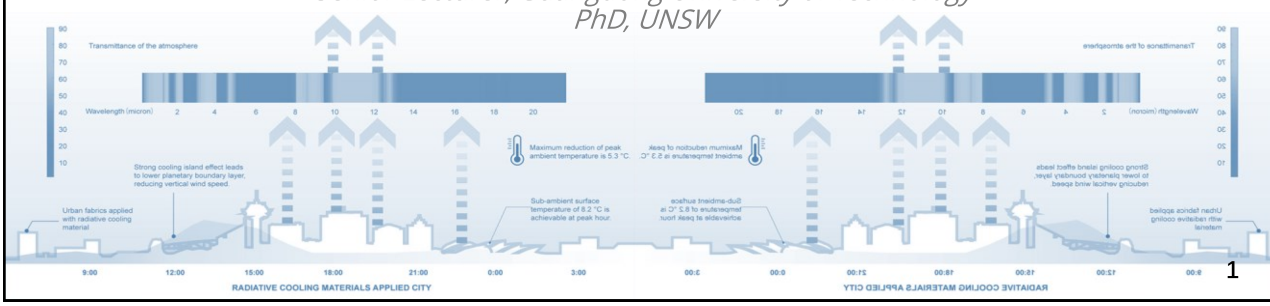
Recent Developments of Super Cool Materials

Dr Jie Feng
Senior Lecturer, Guangdong University of Technology
PhD, UNSW



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Outline

1 Fundamentals and performance
- Basics
- Performance and limitations
- Commercialization
- Impact

2 Further increase the cooling performance
- Integration of fluorescent pigment
- Prevention of pigment aggregation
- Porous morphology

3 Summary and outlook

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Fundamentals and performance

▶ Basics

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Fundamentals

Heat dissipation: $Pout = e \cdot \sigma \cdot T_{roof}^4$

Heat absorption: $Pin = R_{solar} \cdot (1-(r+t)_{short}) + \alpha_{cond+conv} \cdot (T_{ambient} - T_{roof}) + R_{long} \cdot (1 - a_{long})$

- e: Emissivity;
- σ: Stefan-Boltzmann constant
- T_{roof}: Roof surface temperature
- R_{solar}: Solar radiation
- R_{long}: Atmospheric radiation
- $\alpha_{cond+conv}$: Conductive and convective heat transfer coefficient
- R_{long}: Atmospheric radiation
- t: Transmittance
- r: Reflectance
- a: Absorptance

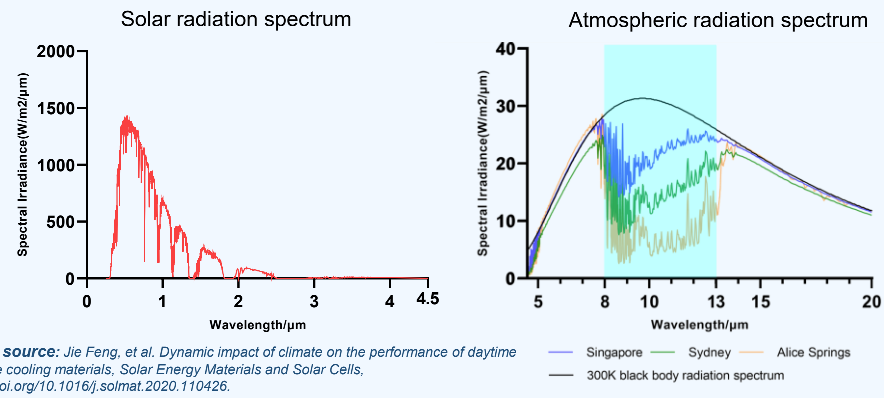

Figure source: Jie Feng, et al. Dynamic impact of climate on the performance of daytime radiative cooling materials, Solar Energy Materials and Solar Cells, https://doi.org/10.1016/j.solmat.2020.110426.

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Fundamentals and performance

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Fundamentals

Heat dissipation: $Pout = e \cdot \sigma \cdot T_{roof}^4$

Heat absorption: $Pin = R_{solar} \cdot (1-(r+t)_{short}) + \alpha_{cond+conv} \cdot (T_{ambient} - T_{roof}) + R_{long} \cdot (1-(r+t)_{long})$

↑Pout	extremely **high emissivity at wavelength between 8 and 13 micrometers** where the atmosphere is transparent.
↓Pin	extremely **high reflectivity in visible and near-infrared wavelengths**
	The selection of optical properties in 4-8 and 13-50um depends on the specific environmental condition

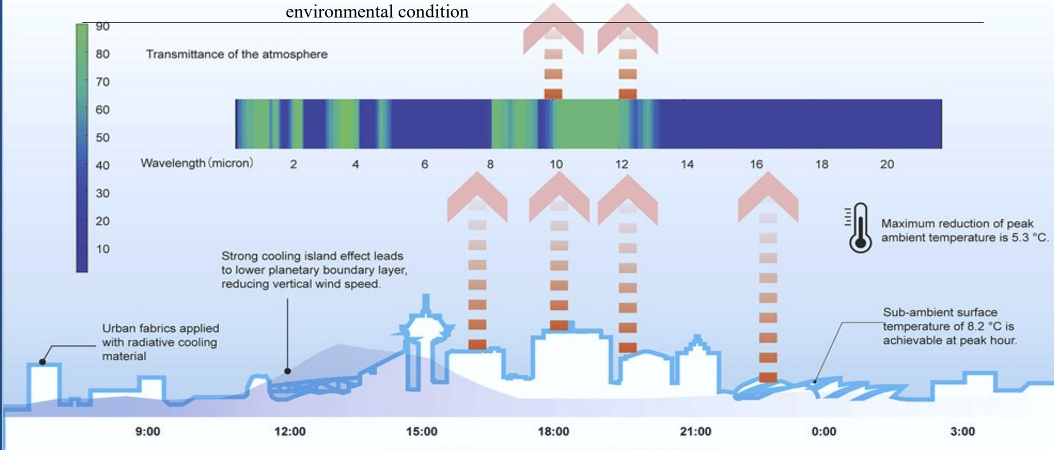

Figure source: Jie Feng, et al. The heat mitigation potential and climatic impact of super-cool broadband radiative coolers on a city scale, Cell Reports Physical Science, https://doi.org/10.1016/j.xcrp.2021.100485.

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Fundamentals and performance

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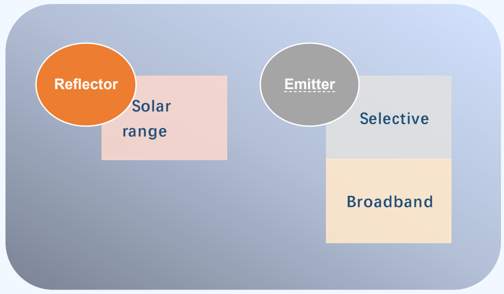
Ideal cooler



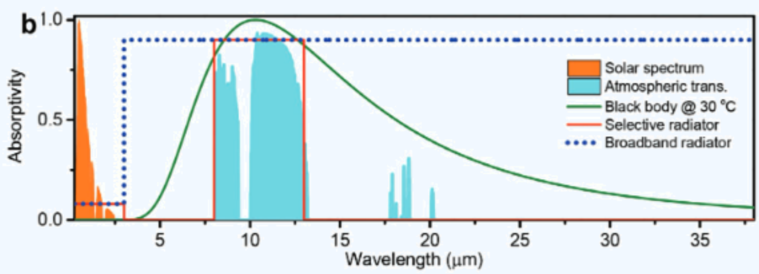


Figure source: *Yang, Y., & Zhang, Y. (2020). Passive daytime radiative cooling: Principle, application, and economic analysis. MRS Energy & Sustainability, 7, E18. doi:10.1557/mre.2020.18*

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Fundamentals and performance

Basics

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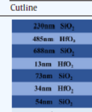
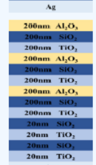
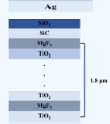
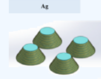
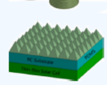
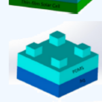
Performance-Photonic crystal

One-dimensional photonic crystal requires electron beam evaporation

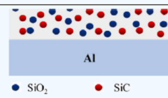
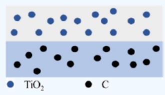
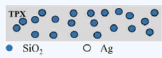
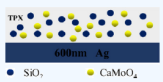
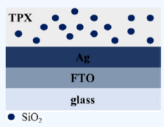
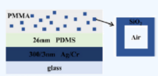
Multi-dimensional photonic crystal requires photolithography

Optical properties and cooling effect of multi-layer photonic radiative cooling structures.

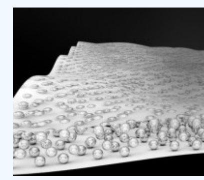
Year	Cooling structure		Optical properties	$\Delta T = T_a - T_r$ (°C)	$P_{net\text{-}cooling}$ (W/m^2)
	Cutline	Description			
2014		Seven layers of alternating HfO_2 and SiO_2(Raman et al., 2014)	R_{solar} = 0.97 ε_{LWIR} = 0.5–0.8	5	40
2017		Combination of SiO_2, TiO_2 and Al_2O_3 layers (Kecebas et al., 2017)	R_{solar} = 0.94 ε_{LWIR} = 0.84	N.A.	100
2013		3 groups of 5 layers of MgF_2 and TiO_2 on a silver substrate, 2 laminated SiC and quartz (Rephaeli et al., 2013)	R_{solar} = 0.965 ε_{LWIR} = 0.1–0.95	N.A.	105
2015		Symmetric conical meta-materials composed of alternating layers of Al and Ge (Hossain et al., 2015)	R_{solar} = 0.97 ε_{LWIR} = 0.99	9	N.A.
2019		The upper surface of PDMS is a pyramid structure (Lee & Luo, 2019)	R_{solar} = 0.95 ε_{LWIR} = 0.98	6.2	20
2020		PDMS films with 2D grating patterns (Song et al., 2020)	ε_{LWIR} = 0.99	N.A.	N.A.

Info source: *Yan Cui, et al. Progress of passive daytime radiative cooling technologies towards commercial applications, Particuology, Volume 67,2022,Pages 57-67,https://doi.org/10.1016/j.partic.2021.10.004.*

Performance-film or coatings including random particles

Year	Cooling structure		Optical properties	$\Delta T = T_a - T_r$ (°C)	$P_{net\text{-}cooling}$ (W/m^2)
	Cutline	Description			
2010		25 µm thick SiC and transparent PE coating containing SiO_2 nanopartcles (Gentle & Smith, 2010)	$R_{solar} = 0.9$ $\varepsilon_{LWIR} = 0.35–0.95$	12–25	N.A.
2016		Acrylic resin randomly doped with TiO_2 and carbon black particles (Huang & Ruan, 2017)	$R_{solar} = 0.9$ $\varepsilon_{LWIR} > 0.9$	6	100
2017		Silvered glass beads were randomly embedded in the polymer matrix (Yao Zhai et al., 2017)	$R_{solar} = 0.96$ $\varepsilon_{LWIR} = 0.93$	8	93
2019		TPX film doped with nano-sized SiO_2 and $CaMoO_4$ particles (Liu, Bai et al., 2019)	$R_{solar} = 0.94$ $\varepsilon_{LWIR} = 0.85$	N.A.	47
2019		Nanoporous SiO_2 microspheres-polymethylpentene (TPX) (Yang, Gao et al., 2020)	$\varepsilon_{LWIR} = 0.91$	4.5	N.A.
2020		SiO_2 nanoshell (Suichi et al., 2020)	$R_{solar} = 0.98$	2.3	N.A.



Info source: *Yan Cui, et al. Progress of passive daytime radiative cooling technologies towards commercial applications, Particuology, Volume 67,2022,Pages 57-67,https://doi.org/10.1016/j.partic.2021.10.004.*

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Fundamentals and performance

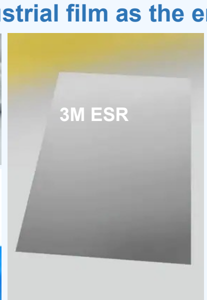
Basics

Performance and limitations

Commercialization

Impact

Performance-industrial film as the emitter



Polyvinyl fluoride (PVF) film
C-H and C-F bonds

Polymethylpentene (TPX)
C-H bond

Polytetrafluoroethylene (PTFE or Teflon)
C-F bond

Acrylic
C-O and C-H bonds

poly(methyl methacrylate) (PMMA)
C-H, and C-O bonds

Polyvinylidene fluoride (PVDF) **C-H and C-F bonds**

Solar Energy, Vol. 17, pp. 83–89. Pergamon Press 1975. Printed in Great Britain

1975

THE RADIATIVE COOLING OF SELECTIVE SURFACES

S. CATALANOTTI, V. CUOMO, G. PIRO, D. RUGGI, V. SILVESTRINI and G. TROISE
Istituto di Fisica Sperimentale dell'Università di Napoli, Via Antonio Tari 3, 80138 Napoli, Italy

(*Received 22 March 1974; in revised form 26 August 1974*)

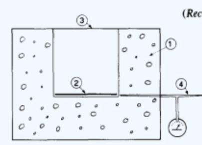


Fig. 4. Schematic drawing of the experimental set-up. 1. Insulating material; 2. Selective radiator; 3. Transparent cover; 4. Thermocouple.

The radiator
The selective radiator has been built by coating a sheet of evaporated aluminum with a thin film (12·5 µm) of TEDLAR, a polyvinyl-fluoride plastic produced by Du Pont de Nemours.

Vibration region	Functional groups	Dominant Group
X – H stretching region (4000-2500 cm^{-1})	C – H, O – H, N – H	N – H
Triple bond region (2500—2000 cm^{-1})	C ≡ N, C ≡ C	C ≡ N
Double bond region (2000-1500 cm-1)	C = C, C = O, C = N	C = O
Finger-print region (crowded region, mainly bending vibration) (1500-600 cm-1)	C – H, C – O, C – N, C – Cl, C – F	Weak but significant overlapping
Skeletal vibration region (600-400++cm^{-1})	Heavy atoms and molecules	

Info source: *Jie Feng, et al. The heat mitigation potential and climatic impact of super-cool broadband radiative coolers on a city scale, Cell Reports Physical Science, https://doi.org/10.1016/j.xcrp.2021.100485.*
A. Aili, Z.Y. Wei, Y.Z. Chen, D.L. Zhao, R.G. Yang, X.B. Yin, Selection of polymers with functional groups for daytime radiative cooling, Materials Today Physics, https://doi.org/10.1016/j.mtphys.2019.100127.

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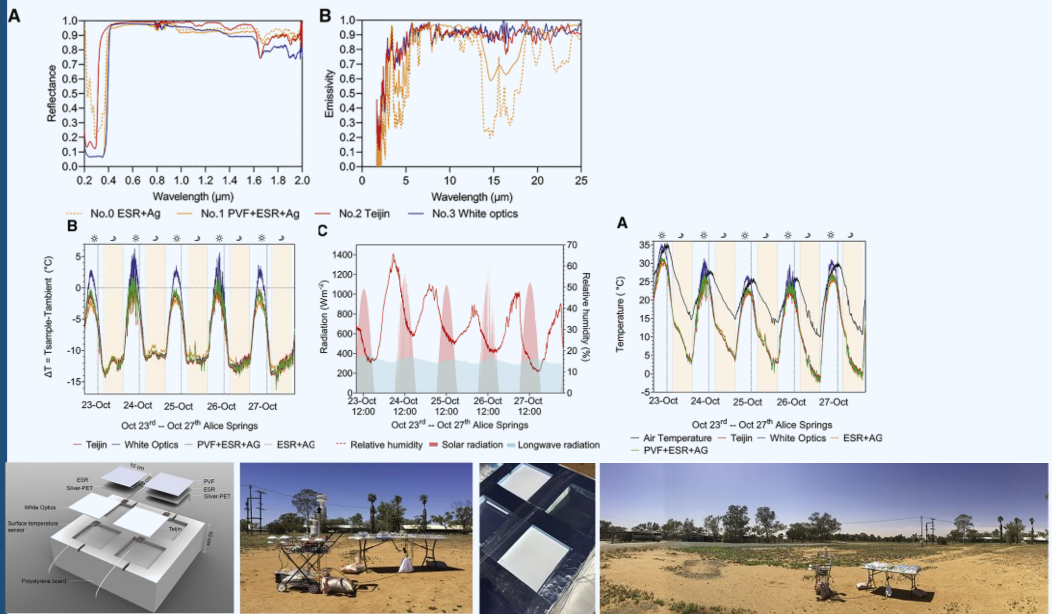
Performance-industrial film



Info source: *Jie Feng, et al. The heat mitigation potential and climatic impact of super-cool broadband radiative coolers on a city scale, Cell Reports Physical Science, https://doi.org/10.1016/j.xcrp.2021.100485.*

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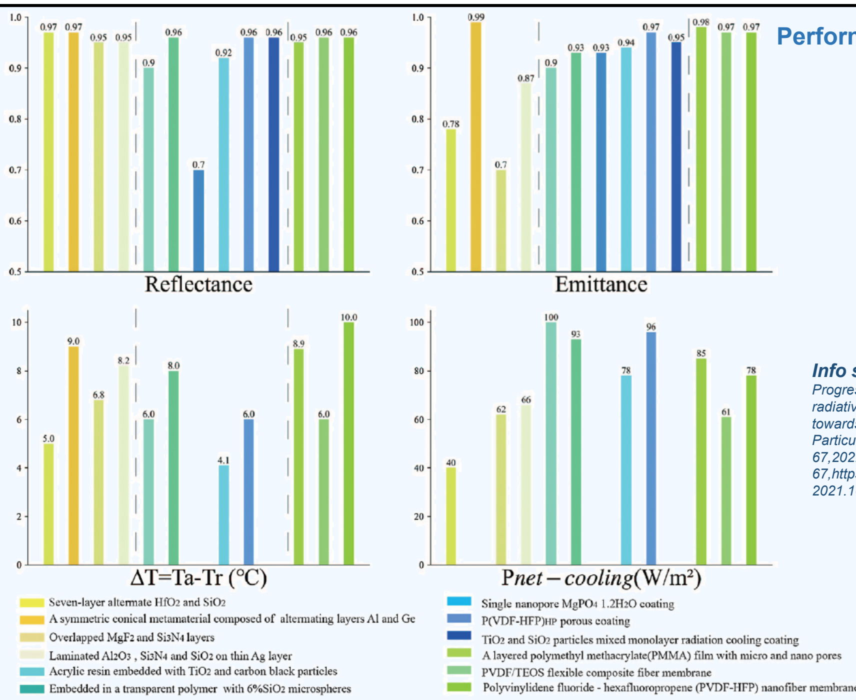
Performance summary



Info source: *Yan Cui, et al. Progress of passive daytime radiative cooling technologies towards commercial applications, Particuology, Volume 67,2022,Pages 57-67,https://doi.org/10.1016/j.partic.2021.10.004.*

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Limitations-Humid climate

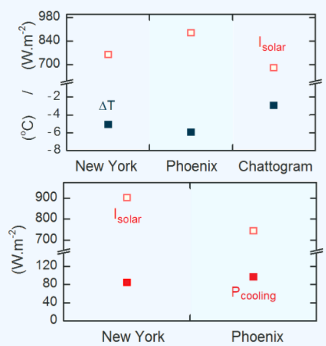
Locations and Weather

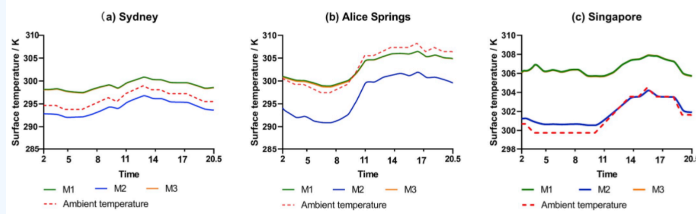
Phoenix (Midlatitude, Arid)
Elevation 349 m, Date: 2018-03-03, Sky clear, Air temperature ~26.5˚ C, TPW ~8mm

New York (Midlatitude, Coastal)
Elevation 85 m, Date: 2018-03-31, Sky clear, Air temperature ~14.5˚ C, TPW ~6 mm

Chattogram (Tropical, Coastal)
Elevation 56 m, Date: 2018-01-10, Fog/Haze, Air temperature ~24˚ C, TPW ~10 mm

*TPW = Total Precipitable water





Info source: △

Jie Feng, et al. Dynamic impact of climate on the performance of daytime radiative cooling materials, Solar Energy Materials and Solar Cells,https://doi.org/10.1016/j.solmat.2020.110426

◁ *J Mandal el al. Hierarchically porous polymer coatings for highly efficient passive daytime radiative cooling. Science.*
DOI: 10.1126/science.aat9513

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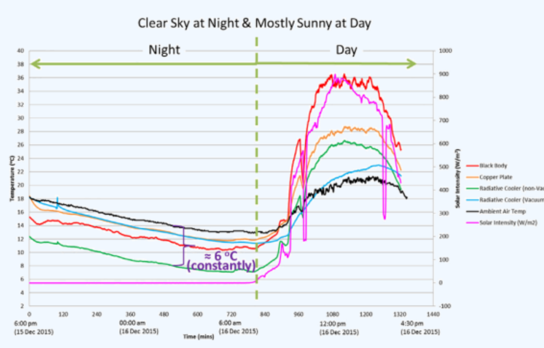
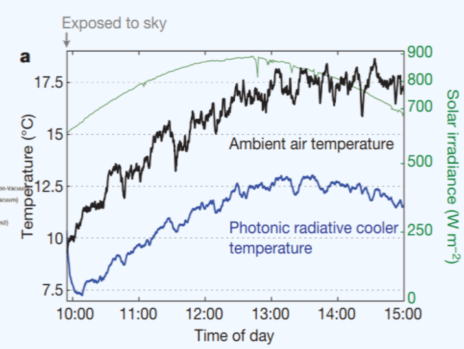
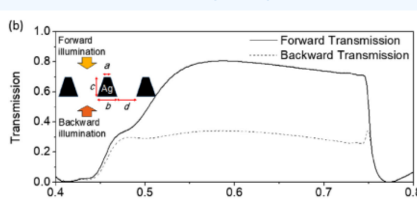
Limitations-Humid climate



Hong Kong



Same material & settings
Stanford, California



Possible solution: asymmetric transmission metallic gratings

△ *C.Y. Tso, K.C. Chan, Christopher Y.H. Chao, A field investigation of passive radiative cooling under Hong Kong's climate, Renewable Energy, https://doi.org/10.1016/j.renene.2017.01.018.*

◁ *Wong, R. Y. M., Tso, C. Y., Chao, C. Y. H., Huang, B., & Wan, M. P. (2018). Ultra-broadband asymmetric transmission metallic gratings for subtropical passive daytime radiative cooling. Solar Energy Materials and Solar Cells, 186, 330-339. https://doi.org/10.1016/j.solmat.2018.07.002*

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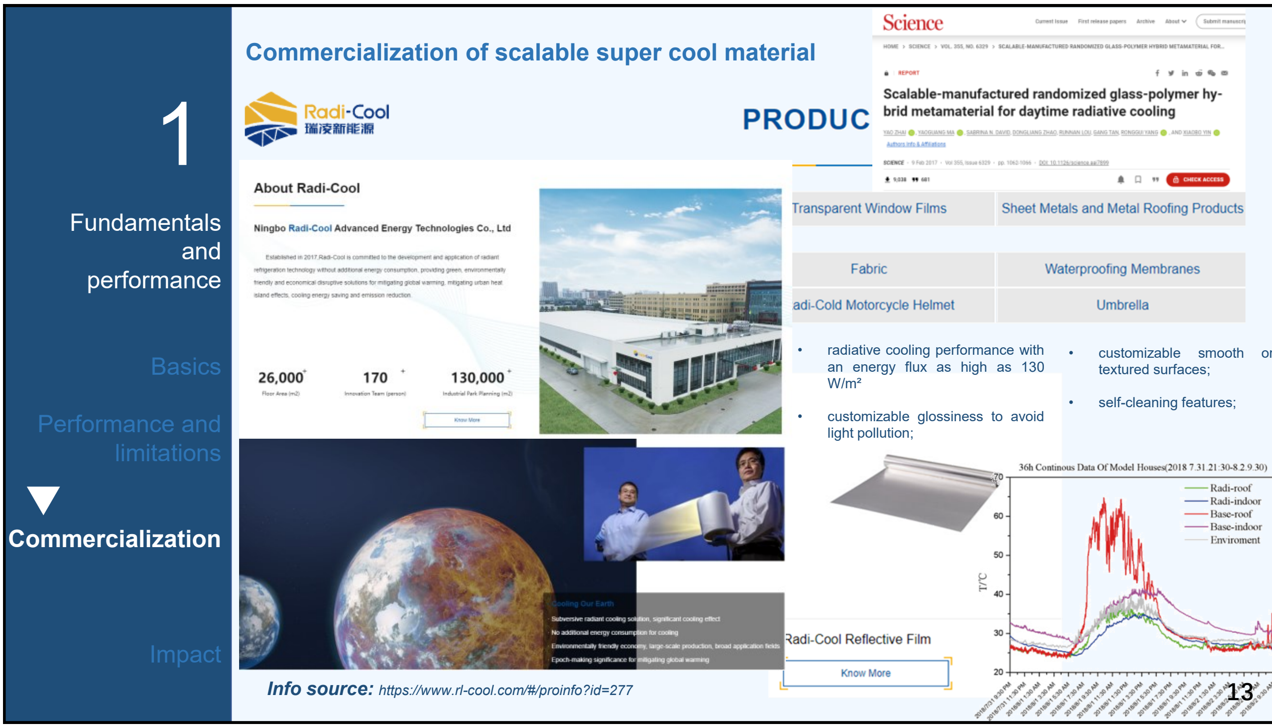

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Commercialization of scalable super cool material
Radi-Cool
瑞凌新能源
PRODUC
About Radi-Cool
Ningbo Radi-Cool Advanced Energy Technologies Co., Ltd
26,000
170
130,000
Science
Scalable-manufactured randomized glass-polymer hybrid metamaterial for daytime radiative cooling
Transparent Window Films
Sheet Metals and Metal Roofing Products
Fabric
Waterproofing Membranes
adi-Cold Motorcycle Helmet
Umbrella
radiative cooling performance with an energy flux as high as 130 W/m²
customizable glossiness to avoid light pollution;
customizable smooth or textured surfaces;
self-cleaning features;
Radi-Cool Reflective Film
Know More
36h Continous Data Of Model Houses(2018.7.31 21:30-8.2 9:30)
Radi-roof
Radi-indoor
Base-roof
Base-indoor
Enviroment
T/C
Info source: https://www.rl-cool.com/#/proinfo?id=277
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Radi-Cool
瑞凌新能源
Big and High Public Buildings
Industrial Plant
Industrial standard plant, plant construction, etc
Transportation
Large and small passenger cars, cars, new energy vehicles, logistics vehicles, etc
Electronic/electrical Equipment
Outdoor Goods
High-end Agriculture and Animal Husbandry
Petrochemical Engineering
Solar Photovoltaic
Enhance photoelectric conversion efficiency and weather resistance
Info source: https://www.rl-cool.com/#/proinfo?id=277
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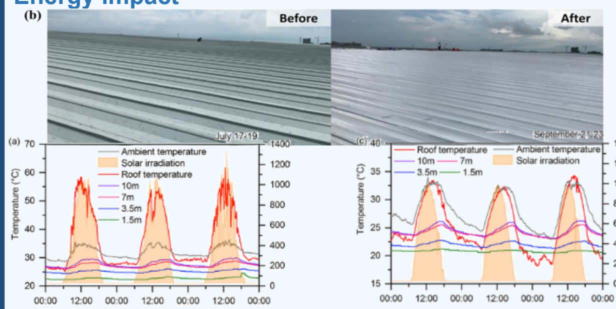
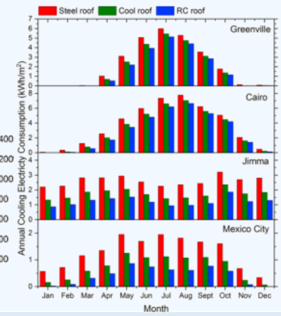
Energy impact





Info source: *Ningsheng Wang, Yinyan Lv, Dongliang Zhao, Wenbo Zhao, Jingtao Xu, Ronggui Yang, Performance evaluation of radiative cooling for commercial-scale warehouse, Materials Today Energy, https://doi.org/10.1016/j.mtener.2021.100927.*

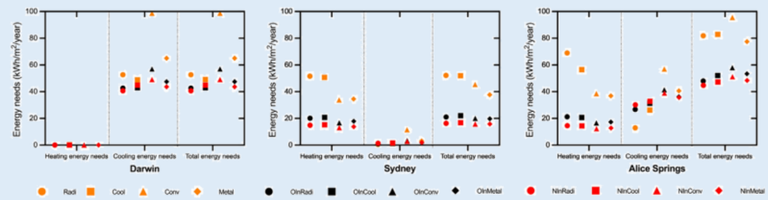


Fig. 8. The annual heating and cooling energy needs for the buildings with different insulation conditions applied with the four roof materials in a) Darwin b) Sydney and c) Alice Springs.

Findings: radiative cooling roof can reduce more the annual energy use in a cooling-dominated climate. With insulation added, the difference in cooling, heating, or total energy needs in buildings with different roof types has been largely decreased. But under cooling dominated climate or climate with mixed heating and cooling, the radiative cooling material still has advantages in reducing the overall energy consumption in buildings.

Info source: *Jie Feng, Maria Saliari, Kai Gao, Mattheos Santamouris, On the cooling energy conservation potential of super cool roofs, Energy and Buildings, https://doi.org/10.1016/j.enbuild.2022.112076.*

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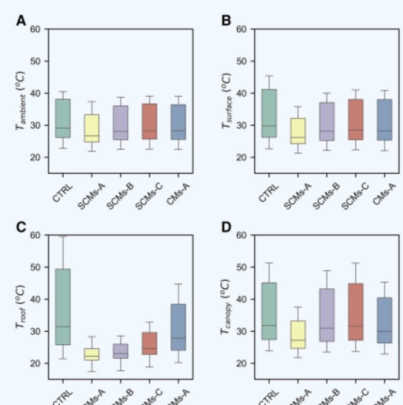
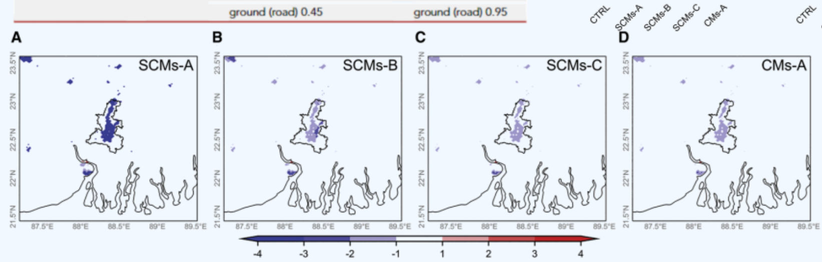
Large scale impact

Table 1. Design of numerical simulation for SCMs

Numerical simulations	Type of roof	Modification of WRF-SLUM in a high-density residential area: Albedo (high-density residential)	Emissivity
Control case (CTRL)	conventional	roof 0.20 wall 0.20 ground (road) 0.20	roof 0.90 wall 0.90 ground (road) 0.95
Implementing case			
SCM-A	super-cool	roof 0.96 wall 0.91 ground (road) 0.71	0.97 for all
SCM-B	super-cool	roof 0.96 wall 0.30 ground (road) 0.40	0.97 for all
SCM-C	super-cool	roof 0.90 wall 0.20 ground (road) 0.20	0.90 for all
Comparison case			
CM-A	cool	roof 0.65 wall 0.60 ground (road) 0.45	roof 0.90 wall 0.90 ground (road) 0.95





Info source: *Jie Feng, et al. The heat mitigation potential and climatic impact of super-cool broadband radiative coolers on a city scale, Cell Reports Physical Science, https://doi.org/10.1016/j.xcrp.2021.100485.*

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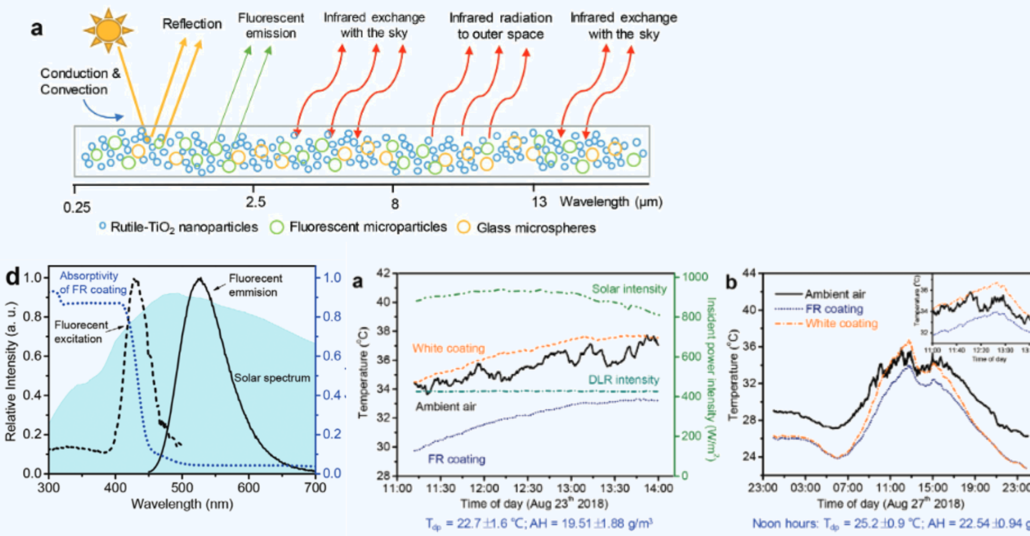
Further increase the cooling performance

▶ **Integration of fluorescent pigment**

Prevention of pigment aggregation

Porous morphology

Integration of fluorescent pigment



Info source: *Xue, X., Qiu, M., Li, Y., Zhang, Q. M., Li, S., Yang, Z., Feng, C., Zhang, W., Dai, J.-G., Lei, D., Jin, W., Xu, L., Zhang, T., Qin, J., Wang, H., Fan, S., Creating an Eco-Friendly Building Coating with Smart Subambient Radiative Cooling. Adv. Mater. 2020, 32, 1906751. https://doi.org/10.1002/adma.201906751*

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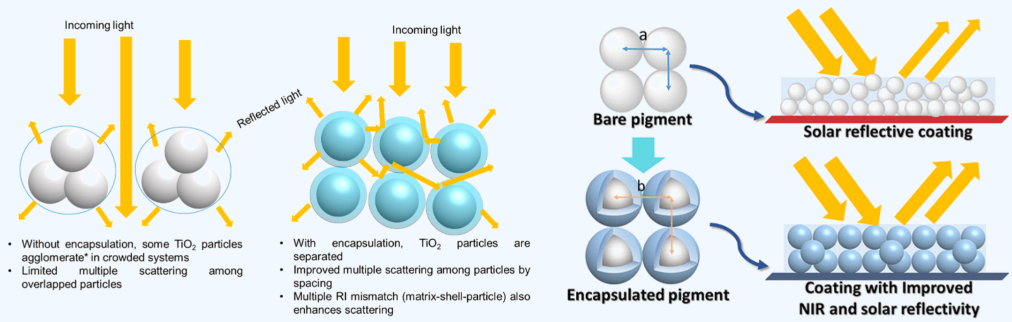
Further increase the cooling performance

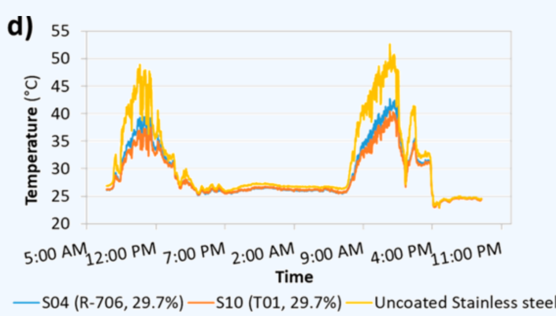
Integration of fluorescent pigment

▶ **Prevention of pigment aggregation**

Porous morphology

Prevention of pigment aggregation





Info source: *Polymer-Encapsulated TiO2 for the Improvement of NIR Reflectance and Total Solar Reflectance of Cool Coatings*
Siming Dong, Jing Yang Quek, Alexander M. Van Herk, and Satyasankar Jana
Industrial & Engineering Chemistry Research 2020 59 (40), 17901-17910
DOI: 10.1021/acs.iecr.0c03412

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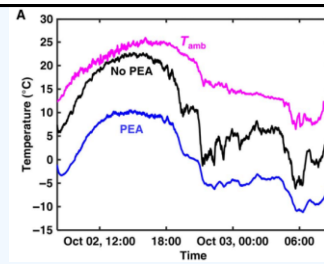
Further increase the cooling performance

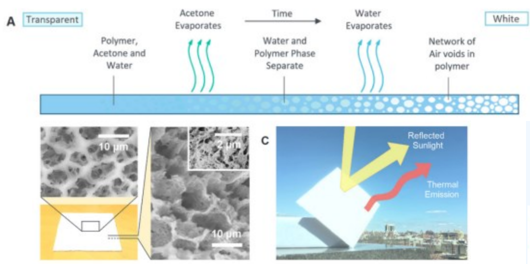
Integration of fluorescent pigment

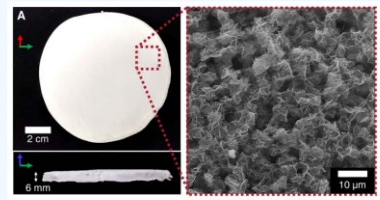
Prevention of pigment aggregation

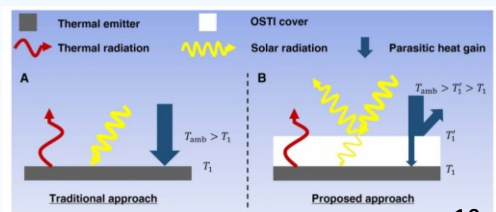
▶ **Porous morphology**

Porous morphology results in high solar reflectance









***Info source**:*

J Mandal el al. Hierarchically porous polymer coatings for highly efficient passive daytime radiative cooling. Science. doi: 10.1126/science.aat9513

A. Leroy et al. High-performance subambient radiative cooling enabled by optically selective and thermally insulating polyethylene aerogel. Science. doi: 10.1126/sciadv.aat9480

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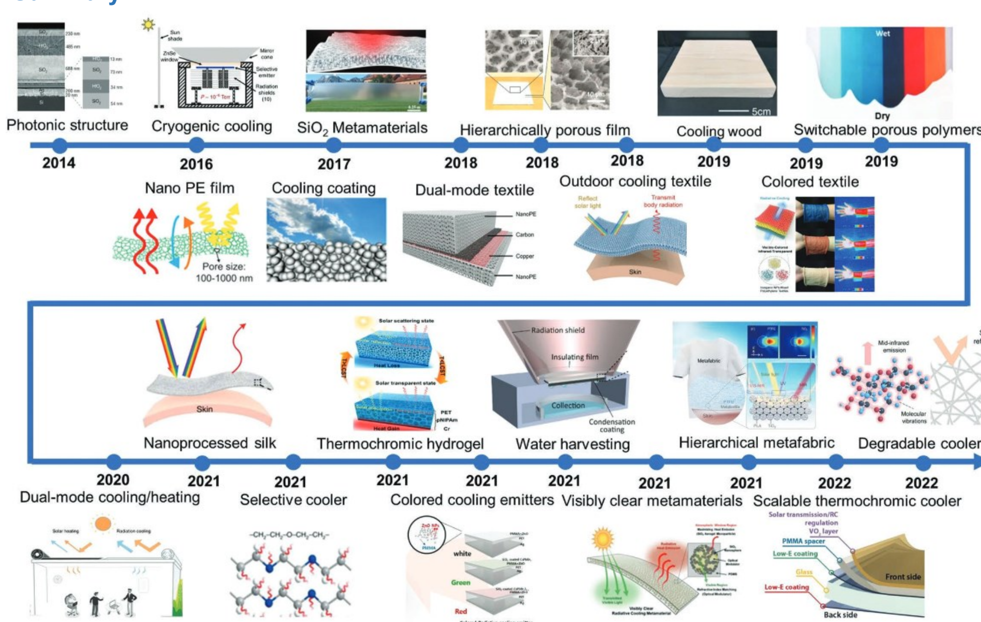
Summary and outlook

- Cooling Performance
- Mechanical Performance
- Weather Fastness
- Aesthetics
- Special Functions

Summary



Info source: *Liu, J., Tang, H., Jiang, C., Wu, S., Ye, L., Zhao, D., Zhou, Z., Micro-Nano Porous Structure for Efficient Daytime Radiative Sky Cooling. Adv. Funct. Mater. 2022, 32, 2206962. https://doi.org/10.1002/adfm.202206962*

Thanks for your attention