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Ultra-broadband asymmetric transmission metallic gratings for subtropical passive daytime radiative cooling

Ross Y.M. Wong[a], C.Y. Tso[a,b], Christopher Y.H. Chao[a,c,*], Baoling Huang[a], M.P. Wan[d]

[a] Department of Mechanical and Aerospace Engineering, The Hong Kong University of Science and Technology, Hong Kong, China
[b] HKUST Jockey Club Institute for Advanced Study, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
[c] Department of Mechanical Engineering, The University of Hong Kong, Hong Kong, China
[d] School of Mechanical and Aerospace Engineering, Nanyang Technological University, Jurong West, Singapore

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ABSTRACT

By simultaneously reflecting solar irradiation and emitting thermal radiation to the cold universe through an atmospheric window lying within 8–13 μm of the electromagnetic spectrum, surfaces could be cooled below ambient temperature under direct sunlight. However, both humidity and cloud coverage can raise the sky emissivity, significantly intensifying thermal emission within the 8–13 μm spectrum. A radiative cooler is strongly absorptive of the additional heat load, and eventually, the cooling capacity drops in a humid environment. In this work, we suggest integrating the cooler with an asymmetric electromagnetic transmission (AEMT) window, which permits outgoing radiative transmission, but reflects incoming radiation of the same wavelengths, so as to recover the cooling performance under a humid climate. This study aims at discussing the working principle of an AEMT enhanced radiative cooler quantitatively as well as demonstrating a feasible design of an AEMT device for radiative cooling applications. First, a theoretical model on the basis of conservation of energy is developed for the prediction of cooling performance of the AEMT enhanced radiative cooling systems. Cooling power is solved for a humid semi-transparent sky condition numerically, which shows that an AEMT window with forward and backward transmittances of 0.8 and 0.4 respectively could restore the cooling power of the passive radiative cooler by 57%. Second, validated finite difference time domain (FDTD) simulations reveal that an AEMT window implemented by near-wavelength tapered metallic gratings could meet the desired transmission ratio (i.e. contrast ratio of 2 within 8–13 μm spectrum) for radiative cooling.

1. Introduction

Space cooling and refrigeration consume over 40% of commercial building energy in Hong Kong [1]. In the refrigeration cycle, energy is spent on transporting heat from the cold side to the hot side. Large amounts of energy and ozone depleting refrigerants have to be used in the energy conversion process. Conversely, passive cooling technologies, which do not require any energy input in any form but still provide a desirable cooling performance, are more sustainable and environmentally friendly. Radiative cooling [2–4] is one of the most extensively researched areas in the literature. Early work on radiative cooling focused on nighttime performance and its principle, development and applications have been comprehensively reviewed [2–4]. However, nocturnal radiative cooling cannot meet the peak cooling demand during daytime, limiting space cooling application in buildings. Thanks to recent breakthroughs in daytime passive radiative cooling [5], Goldstein et al. (2017) cooled water by 3–5 °C below dry-bulb temperature with serially connected passive radiative cooling panels during the daytime [6]. By rejecting heat to passively chilled water, the pre-condensed temperature of the refrigerant can be lowered, resulting in a higher coefficient of performance (COP) for the refrigeration cycle. Building energy simulations (BESs) have demonstrated that enhanced system performance can reduce electricity consumption for space cooling of an office building in summer by 21% [6]. Also, a similar BES-based study unveiled an energy saving opportunity of 45% or more with radiative cooling systems in buildings in various American cities [7]. Obviously, a passive daytime radiative cooler offers a promising space cooling scheme for future smart green buildings. In addition, it shows great impact on the radiative cooling of solar cells [8,9], personal thermal management systems [10] and thermo-regulatory clothing [11].

A passive daytime radiative cooler has a sky-facing surface, which

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* Correspondence to: Faculty of Engineering, The University of Hong Kong, Room 501, Haking Wong Building, Pokfulam Road, Hong Kong, China.
E-mail address: cyhchao@hku.hk (C.Y.H. Chao).

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Nomenclature

c	speed of light [m/s]
h	Planck's constant [J-s]
h_c	combined conductive and convective heat transfer coefficient [W/m^2-K]
i	iteration step [dimensionless]
I	radiance/ irradiance [W/m^2-nm]
k	index for scattering events [dimensionless]
k_B	Boltzmann constant [J/K]
L	length [m]
n	index for time steps [dimensionless]
p	periodicity [m]
P	radiative heat flux; radiative power [W/m^2]
T	temperature [K]
x, y, z	Cartesian coordinates [m]
$\mathbf{A}$	surface vector [m^2]
$\mathbf{E}$	electric field intensity [V/m]
$\mathbf{H}$	magnetic field intensity [A/m]
$\mathbf{S}$	Poynting vector [W]
$\mathbf{x}$	position vector [m]

Greek letters

ε	absorptivity/ emissivity [dimensionless]
η	relative permittivity [dimensionless]
θ	acute angle [dimensionless]
λ	wavelength [m]
ρ	reflectance [dimensionless]
τ	transmittance [dimensionless]
ω	angular frequency [/s]
Ω	solid angle [dimensionless]
Δt	time step [s]
Δx	cell size [m]
$\Delta\lambda$	resolution for wavelength [m]

Subscripts

0	incidence
∞	high frequency limit
a, b	lower and upper values respectively
amb	the ambient
atm	the atmosphere
AM1.5G	Air mass 1.5G solar spectrum
b	backward transmission
bb	blackbody
c	cooler
cl	cooling
cut-off	cut-off
d	damping
f	forward transmission
h	high
i	iteration step
in	incoming
l	low
min	minimum
net	net
p	plasma
rad	thermal radiation
ref	reabsorbed radiation due to AEMT window reflection
s	substrate
ss	steady state
sun	the sun
α	absorption
ρ	reflection
τ	transmission

can strongly reflect solar irradiation and emit mid-infrared (MIR) radiation to the cold universe of 3 K through the transparent atmospheric window lying within 8–13 µm of the electromagnetic spectrum. Rephaeli et al. (2013) predicted, theoretically, that a metallic-dielectric photonic structure, behaving as a solar mirror and MIR emitter, would be capable of daytime radiative cooling with a net cooling power over 100 W/m^2 [12]. Raman et al. (2014) demonstrated radiative cooling under direct sunlight using a photonic radiative cooler made of 7 layers of alternating silicon dioxide (SiO_2) and hafnium dioxide (HfO_2) thermal emitter backed by a silver (Ag) solar reflector, displaying high solar reflectance of 0.97 and high 8–13 µm emittance, producing cooling power of 40 W/m^2 and a temperature reduction of nearly 5 °C below ambient [5]. Chen et al. (2016) reported an ultra-large temperature reduction of 42 °C under peak solar irradiance, achieved by a vacuumed radiative cooler made of a silicon nitride (Si_3N_4) 8–13 µm emitter and an aluminum (Al) solar reflector [13]. Srinivasan et al. (2016) characterized the absorption/emission spectrum of polydimethylsiloxane (PDMS) thin film atop a gold (Au) coated substrate by Fourier Transform Infrared (FTIR) spectrometry and observed strong emission within the 8–13 µm spectrum [14]. Kou et al. (2017) revealed a skyrocketing cooling power of 127 W/m^2 and a temperature reduction of 8.2 °C in daytime operation with a fused silica coated by PDMS and Ag on the top and bottom sides respectively [15]. Gentle and Smith (2011) discussed the use of silicon carbide (SiC) and SiO_2 micro-particles dispersed in infrared transparent polymers for enhanced emission within the 8–13 µm spectrum [16], and Zhai et al. (2017) optimized the particle size and fabricated a scalable manufactured SiO_2 doped polymeric radiative cooler, recording a high cooling power of 93 W/m^2 [17]. Apart from ordinary materials, plasmonic and biomimetic materials are more engaging alternatives. A plasmonic thermal selective surface can be fabricated by patterning micro-pillars on Al plate, providing a predicted cooling power of 116 W/m^2 [18]. A simplified plasmonic structure made of Ag coated micro-patterned Si substrate also gives comparative cooling power [19]. A biomimetic triangular prism patterned surface inspired by the thermo-regulatory effect of the triangular hairs on the Saharan silver ant significantly enhances both the optical reflection and MIR emission of a uniform surface [20,21].

So far, successful field investigations on daytime radiative cooling have been carried out in arid American cities where 8–13 µm atmospheric transmittance is high [5,13,15,17]. Also, Goldestein et al. (2017) emphasized the importance of an arid environment to radiative fluid cooling [6]. However, many cities, such as Hong Kong and Singapore, which are confronting increasing demand for electricity and space cooling, are hot and humid. For these low-to-mid latitude cities under non-arid climates, the daytime radiative cooling potential has remained doubtful. Hossain and Gu (2016) theoretically evaluated the performance in two different cities in Australia, concluding a poorer cooling performance under a low infrared transparency sky [22]. Tso et al. (2017) tested a photonic radiative cooler identical to the one proposed in Ref. [5] under the hot and humid climate conditions in Hong Kong [23], while Bao et al. (2017) investigated solar reflective 8–13 µm emissive radiators in Shanghai, where the temperature and the relative humidity varied within 24–32 °C and 50–70% respectively during measurement [24]. Both found the surface temperature could drop below ambient by a few °C at nighttime but it remained higher than ambient during daytime [23,24]. Obviously, humidity and sky clearness play crucial roles in radiative cooling performance. In highly humid environments, the transparency of the atmospheric window can be lost and downwelling longwave radiation can increase substantially. Both classical and recently developed sky emissivity models show

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