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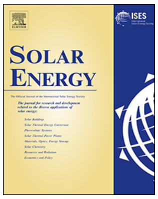

Active daytime radiative cooling using spectrally selective surfaces for air conditioning and refrigeration systems

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ABSTRACT

Surfaces that exhibit high reflectivity at short (solar) wavelengths and high emissivity at long (terrestrial) wavelengths can experience net radiation cooling, even when subjected to high levels of solar irradiation. A model is developed to quantify passive cooling rates provided by such a surface for an air conditioning application. The model is then extended to predict the performance of a new, photovoltaic-powered air conditioning or refrigeration system where the selective surface actively rejects heat from the air conditioning unit by radiation and convection. It is shown that use of spectrally selective surfaces that have been recently suggested for passive cooling might be better used actively to more effectively: match cooling loads, reduce the required heat rejection surface area, and increase the heat transferred from Earth through the atmospheric window. The proposed active daytime radiative cooling concept also has advantages over more traditional air conditioning approaches.

1. Introduction

There has been considerable recent interest in developing radiation surfaces that exhibit sharp spectral variations of emissivity, absorptivity and reflectivity so as to simultaneously (*i*) inhibit absorption of short wavelength solar irradiation and (*ii*) promote long wavelength surface emission. Achieving the desired spectral properties allows for passive daytime radiative cooling (PDRC) of the surfaces, even when the surfaces are exposed to direct solar irradiation (Chang et al., 1995; Chen et al., 2016; Raman et al., 2014). In addition to contributing to daytime radiation heat losses, high surface emission within the atmospheric window ($8\,\mu\text{m} < \lambda < 13\,\mu\text{m}$) is desirable because terrestrial (low source temperature) radiation in this wavelength range is relatively unaffected by absorption and scattering as it propagates upward through the atmosphere to deep space (Granqvist and Hjortsberg, 1981; Nilsson and Niklasson, 1995). It has been suggested that widespread use of spectrally selective surfaces that are characterized by low solar absorptivity and high emissivity can provide a pathway to energy sustainability, and could reduce global temperatures (Chu et al., 2017; Wong, 2017).

It has been reported that the first measured reduction of the temperature of a surface that is exposed to direct sunlight to values below that of the ambient air was by Raman et al. (2014). Temperature drops of approximately 5 °C were achieved by using a photonic surface that exhibited desired radiative properties as described by Granqvist and Hjortsberg (1981) and the references therein. Subsequently, Chen et al. (2016) achieved temperature reductions in excess of 40 °C relative to the ambient while the surface was exposed to peak solar irradiation. This large temperature reduction was accomplished by meticulously insulating the surface to minimize conduction and convection gains from the environment. Recently, Zhai et al. (2017) measured the temperature decrease of a small volume of liquid water, to 8 °C below that of the ambient, by placing a spectrally selective film in contact with the underlying water layer and exposing the filled container to direct solar irradiation. The film was a polymer-glass bead composite backed with a reflective metal layer that was reported to be amenable to low-cost, high-volume production. Additional materials designed to provide passive temperature reduction of surfaces exposed to solar irradiation have been recently proposed (Bao et al., 2017; Huang and Ruan, 2017; Kecebas et al., 2017).

1.1. Temperature reduction versus cooling rate

Because of (*i*) their ability to achieve sub-ambient temperatures when exposed to direct solar irradiation and (*ii*) their potentially inexpensive manufacture, the recently developed spectrally selective surfaces and films have been proposed for passive daytime refrigeration as well as passive daytime cooling of automobiles, buildings and other infrastructure by reducing interior temperatures to sub-ambient values that are approximately equal to those of the adjoining cold spectrally selective surfaces (Chang et al., 1995; Fernandez et al., 2015; Lu et al.,

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Nomenclature

A	area (m^2)
C_1, C_2	radiation constants for Planck distribution
COP	coefficient of performance
E	emissive power (W/m^2)
E_λ	spectral emissive power ($W/m^2\,\mu m$)
g	gravitational acceleration (m/s^2)
G	irradiation (W/m^2)
h	convection heat transfer coefficient ($W/m^2\,K$)
k	thermal conductivity ($W/m\,K$)
L	characteristic length (m)
Nu_L	Nusselt number ($= hL/k$)
P	perimeter (m)
Pr	Prandtl number (ν/α)
q	heat rate (W)
q''	heat flux (W/m^2)
Ra_L	Rayleigh number ($= g\beta(T_s - T_\infty)L^3/\nu\alpha$)
Re_L	Reynolds number ($= u_\infty L/\nu$)
T	temperature (K)
u_∞	ambient velocity (m/s)
$\dot{W}$	rate of work (W)

Greek

α	absorptivity, thermal diffusivity (m^2/s)
β	thermal expansion coefficient (K^{-1})
ε	emissivity
η	efficiency
λ	wavelength (μm)
ν	kinematic viscosity (m^2/s)
σ	Stefan Boltzmann constant

Subscripts

atm	atmosphere
AW	atmospheric window
b	blackbody
c	cooling, cold
F	forced convection
h	hot
N	natural or free convection
net	net
pv	photovoltaic
rad	radiation
s	surface
S	solar
sky	sky
t	total
λ	spectral
∞	ambient

2016; Raman et al., 2017; Vall and Castell, 2017). Importantly, however, all radiation surfaces designed for PDRC provide their highest cooling rates (q_c) when their temperatures are relatively high. Low surface temperatures (corresponding to low temperatures in the refrigerated or air conditioned space) can be achieved only when the surface is insulated from, for example, the volume (that is, the refrigerated or air conditioned space) or material to be cooled ($q_c \to 0$). Hence, the thermal behavior of PDRC surfaces (smaller cooling rates at lower temperatures of the refrigerated or air conditioned space) runs counter to the demands of nearly all air conditioning and refrigeration applications for which the highest cooling loads correspond to the lowest room or refrigeration temperatures. Therefore, the notion that PDRC refrigeration or air conditioning might be widely used in practical applications is in need of closer attention, and more effective usage of the recently developed spectrally selective surfaces might be made.

Based on the preceding discussion, spectrally selective surfaces that have been recently proposed for PDRC might be more effectively deployed as *hot* (relative to the ambient temperature) heat rejection surfaces used in conjunction with established refrigeration and air conditioning hardware in order to both (*i*) provide high refrigeration or air conditioning cooling rates when the temperatures of the refrigerated or air conditioned spaces are low and (*ii*) increase heat rejection from Earth through the atmospheric window. More specifically, the identical spectrally selective surface that exhibits high reflectivity at short (solar) wavelengths, and high emissivity at long (terrestrial temperature)

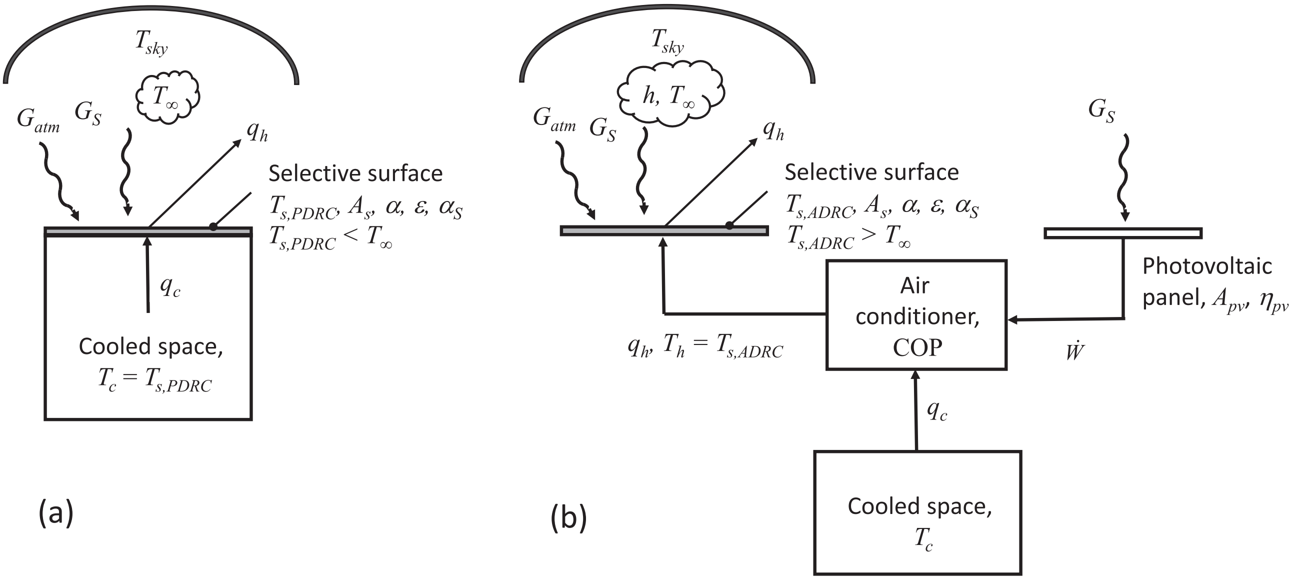

Fig. 1. Schematic of the cooling scenarios showing the relevant heat transfer and thermodynamic processes. (a) Passive ($T_c = T_{s,PDRC} < T_\infty$) operation. (b) Active ($T_{s,ADRC} > T_\infty > T_c$) operation.