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A review of clear sky radiative cooling developments and applications in renewable power systems and passive building cooling

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ABSTRACT

Although nocturnal radiative cooling has been known for centuries, providing sub-ambient radiative cooling during daytime was a challenge until recent years. Recent advances in nano-fabrication technologies, have made it possible to manufacture structures with tailored radiative properties for various energy applications like daytime clear sky radiative cooling. It has been shown that photonic and plasmonic selective emitters can be tuned efficiently to emit heat through clear sky to the outer space and cool terrestrial objects providing passive cooling. There is a renewed interest in clear sky radiative cooling among researchers. Providing continuous day and night sub-ambient cooling and dissipation of low grade heat from renewable power systems without use of water or external energy under direct sunlight and other applications have made clear sky radiative cooling a hot research topic.

This paper reviews relevant publications on clear-sky radiative cooling methods. An overview of radiative cooling fundamentals and a detailed literature survey of published studies on selective emitter structures for daytime and nighttime cooling purposes is presented. Furthermore, a detailed energy analysis is performed identifying key performance indicators and evaluating the cooling performance under various conditions. Findings from studies that have used empirical equations for numerical energy analysis and selective emitter structure designs for daytime and nighttime applications are summarized in tables for easy comparison.

1. Introduction

Radiative heat transfer is the most common form of energy transport in the universe. Practically, all objects at finite temperatures emit electromagnetic radiation. From the thermal radiation point of view, the outer space behaves as a blackbody at a temperature close to absolute zero. Such a low temperature makes the universe as the ultimate heat sink. In the case of extra-terrestrial applications, radiative cooling is the principal way to dissipate excess heat from devices [1]. Moreover, radiative cooling during the night keeps the Earth at its livable temperature. It provides the necessary living conditions for certain species like Saharan silver ants to be able to tolerate harsh desert hot days [2]. Radiative cooling has the potential to compensate problems raised by global warming during recent years [3,4]. However, the presence of the atmosphere significantly inhibits this radiative transfer between structures on the earth's surface and the space.

The earth's atmosphere is a mixture of several gases, mostly N_2, O_2, CO_2, and water vapor. It is a semitransparent medium that can absorb, emit and scatter radiation. The radiative properties of the atmosphere are strongly wavelength dependent. The clear sky atmosphere has a transparency window for electromagnetic radiation in the 8–13 µm wavelength range, particularly when the humidity is low. This atmospheric window also coincides with the peak thermal radiation wavelengths at typical ambient temperatures. Therefore, if appropriate surface thermal radiative properties are met and under proper atmospheric conditions, it is possible to dissipate heat from a terrestrial structure to the outer space by radiation. The key requirement for sub-ambient temperature radiative cooling is emitting radiation selectively within the atmospheric window and suppressing emission/absorption for wavelengths outside this range. Therefore, clear sky cooling presents an opportunity of cooling buildings and other structures by radiation, reducing water consumption in conventional and solar thermal power plants by dry cooling, and refrigeration of food and medicine in remote areas.

Radiative cooling during clear nights in tropical and subtropical areas, for building cooling and water desalination by freezing has been used for several centuries in the past [5–7]. In ancient Iran and India more than 2000 years ago, clear sky radiative cooling was employed in ice making basins and Yakh-Chal (i.e. the ice pit) to produce and store ice even though the ambient temperature was higher than the freezing

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Nomenclature

A	Empirical constant
B	Empirical constant
H	Heat transfer coefficient [W/m^{2}K]
$\breve{h}$	Planks constant = 6.623 × 10^{-34} [J s]
I	Intensity [W/m^{2}μm st]
P	Water vapor pressure [kPa]
$\dot{P}$	Heat flux [W/m^2]
T	Temperature [K]
V	Wind speed [m/s]
c_0	Speed of light in vacuum = 2.998 × 10^8 [m/s]

Subscripts

A	Atmosphere
Atm	Atmospheric
Av	Average
Bb	Blackbody
C	Convective & Conductive
Dp	Dew point
Rad	Radiative
S	Surface
Solar	Solar
Tot	Total

Greek notations

α	Absorptivity
ε	Emissivity
τ	Transmissivity
ρ	Reflectivity
θ	Zenith angle
λ	Wavelength

point [8,9]. As mentioned by Eriksson and Granqvist [7], the first scientific disclosure of such phenomenon was presented by Arago in 1828. Arago reported 6–8 °C temperature drop below ambient temperature for small masses of grass, cotton and quilt placed outdoor in a calm and serene night. In 1959, Head [10] proposed the use of selective infrared (IR) emitters that could be used to enhance the radiative cooling effect during nighttime for the first time. Since that time, researchers have investigated various designs to enhance the radiative cooling phenomenon and its use in different applications.

Nighttime radiative cooling or nocturnal cooling has been investigated broadly during past decades, and its feasibility has been successfully examined by various researchers. There are two general designs available for nighttime radiative coolers. The first method usually consists of a near blackbody emitter that emits strongly in almost the entire thermal spectrum. A thermal blackbody emitter attains a high radiative heat flux (up to 120 W/m^2 [11]) at temperatures close to ambient temperature under a clear sky. But, the inverse effect of radiative thermal absorption at wavelengths outside the atmospheric window limits the minimum attainable temperature in the range of 6–8 °C below ambient temperature. In order to reduce the unfavorable thermal absorption for sub-ambient temperature applications, the second approach is to use a metallic mirror (usually Aluminum or Silver) covered by a thin layer of material that is absorbing/emitting only inside the atmospheric window and transparent for wavelengths outside the 8–13 μm range. The mirror reflects the unfavorable irradiation while the emitter part dissipates the thermal energy to the outer space by radiation inside the atmospheric window range. Thin films of polymers, pigmented paints, metal oxides, and gas slabs as well as multilayer semiconductors and metal-dielectric photonic and plasmonic structures have been proposed as the emitting top part.

Achieving radiative cooling during daytime is more challenging, due to the incident solar radiation. However, since almost all of the solar radiation is in a wavelength range below the atmospheric window a selective emitter that reflects thermal radiation at short wavelengths (below 2.5 μm) and has a high emissivity inside the atmospheric window can produce daytime cooling. Initial attempts to achieve these properties were made by using a radiative cover shield on top of a cooler [12–15]. The cover shield reflects the solar irradiation and at the same time is transparent to the long wavelengths inside the atmospheric window, allowing the radiative cooler beneath it to emit heat to the outer space during daytime. Foils made of polyethylene covered or doped by TiO_2, ZnS and ZnO have been suggested by different researchers [12–15]. However, high solar reflectance and at the same time high IR transmittance are not easily obtained and, thus, none of the experiments by this method have resulted in reaching sub-ambient temperatures under direct sunlight. Recently, a research group at the Stanford University has produced several publications [16–22] demonstrating effective radiative cooling under direct sunlight, using nanostructured photonic coolers. In their designs, the desired radiative profiles are produced by combining a top layer that is a strong emitter in the atmospheric window and transparent to solar radiation with a supporting back reflector, which reflects almost all the incident solar radiation. Similar approach has been adopted with other researchers to achieve daytime radiative cooling. As another successful example, Zhai et al. [23] fabricated a daytime cooling structure using a polymer embedded with micron sized dielectric spheres on top a silver substrate as the back reflector.

The application and potential of clear sky radiative cooling as a passive cooling option for buildings has been investigated in several recent review papers [24–26]. Nwaigwe et al. [27] presented an overview of nocturnal cooling for buildings. They studied the performance of nighttime radiative coolers in different locations, and concluded that for most locations it is possible to reach up to 40 W/m^2 cooling power during clear nights. Lu et al. [28] performed a comprehensive survey of clear sky radiative cooling applications in buildings. Discussions were presented on cooling structures, system configuration and capabilities and limitations of radiative cooling to meet the cooling load of buildings in their paper. Vall and Castell [29] summarized the radiative cooling theory, application of selective emitters, and studies presenting theoretical calculations as well as cooler prototypes in a review paper. Recently, Hossain and Gu [30] and Sun et al. [31] reviewed the fundamentals, progress in new materials and structural designs for radiative coolers. The common area of previous published review papers in clear sky radiative cooling was mostly the application of radiative cooling in buildings. However, the potential of clear sky radiative cooling in dissipating low grade heat from surfaces to the outer space passively, especially for renewable energy power systems is not covered comprehensively in those reviews. The goal of the present paper to present an up to date status of the cooling structures and highlight the potential use of this technique in renewable energy power systems as well as buildings. This review focuses on a detailed coverage of the clear sky radiative cooling technology. The publications on radiation heat balance modeling of terrestrial structures facing the sky, measurement and modeling of atmospheric and solar irradiation, classification of selective emitter structures proposed for daytime and nighttime radiative cooling, applications of radiative cooling in buildings, and improvement potential of renewable energy power systems are reviewed. Also, a numerical analysis is presented to identify key cooling performance indicators and to evaluate the expected radiative cooling capacity under various conditions.

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