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A field investigation of passive radiative cooling under Hong Kong's climate

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ABSTRACT

This paper discusses the feasibility of cooling using radiation under Hong Kong's hot and humid climate. Three different designs of a passive radiative cooler were studied in this work. The three designs include non-vacuum, and vacuum with seven potassium chloride (KCl) IR-Pass windows as well as one system with a single KCl IR-Pass window. The coolers were examined during daytime and night time operation as well as under different sky conditions, such as clear, cloudy and partly cloudy. Investigation was mainly based on the temperature difference between the radiative cooler and ambient air. The experimental results showed that the passive radiative cooler with seven KCl windows and the cooler design without vacuum provided a satisfactory cooling effect at night (i.e. the ambient air temperature was reduced by about 6–7 °C), but the coolers could not produce a cooling effect during daytime under any of Hong Kong's weather conditions. The same results were obtained for the passive radiative cooler with the single KCl window during daytime operation. However, the cooling capacity of the passive radiative cooler design without vacuum under a clear night sky achieved 38 W/m^2.

1. Introduction

More than 30% of electricity consumption in the residential and commercial sectors is for space conditioning in Hong Kong [1]. Reducing the energy consumption for space conditioning is essential to develop energy-efficient buildings. Among the various techniques for space conditioning, passive radiative cooling is very attractive since it requires no electricity and is environmentally friendly [2–16]. Passive radiative cooling is a phenomenon utilizing the properties of the Earth's atmosphere that consists of many different gases, and each gas will absorb Electromagnetic (EM) radiation with specific wavelengths. Combining the absorption spectrum of the gases, there exists transparent windows, called atmospheric windows, where EM waves can pass through easily. Besides the window for visible light, there is also an infrared atmospheric window within the wavelength of 8–13 μm. The peak of the black-body spectrum of normal ambient temperature, about 300 K (27 °C), is also within this range. It means that an object under normal ambient temperature will emit EM radiation mainly within 8–13 μm and the EM radiation can pass freely through the atmosphere.

Radiation cooling to the night sky is based on the principle of heat loss by long-wave radiation from one surface to another body at a lower temperature. Roofs of buildings radiate heat, day and night, at an average rate of up to 75 W/m^2 [15]. During the day, this is offset by solar radiation gains on the roof, however, at night, this heat loss has the ability to cool air or water as roofs can experience a temperature drop of 6–20 °C below ambient. The infrared atmospheric window is a path from the land-sea surface of Earth to space. At the scarcely absorbed continuum of wavelengths (8–13 μm), the radiation emitted by the Earth's surface into a dry atmosphere, and by the cloud tops, mostly passes unabsorbed through the atmosphere and is emitted directly to space. This is because the infrared absorptions of the principal natural greenhouse gases (CO_2 and H_2O) are outside of this range. The effect of this radiant heat leaving the surface of the Earth can easily be seen on some mornings after a clear night in temperate climates. A layer of frost will form on rooftops and on automobiles even though the outdoor air temperature is well above freezing. This frozen condensation is proof that the rooftops lost heat by radiation to the night sky faster than the surrounding warmer air could replace that

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heat by natural convection. The passive radiative cooling below ambient air temperature has been well-demonstrated at night [4–7,10,11,16].

In 1979, Michell and Biggs first investigated the cooling of small buildings at night by radiation loss to the sky [2]. They monitored the thermal performance of two huts: one roofed with galvanized steel decking painted white, while the other had aluminum decking to which aluminized 'Tedlar' sheet had been glued. It was found that the hut with the painted roof was cooled better than that with the 'Tedlar' covered roof. A cooling power of about 22 W/m^2 was achieved at a roof temperature of 5 °C with the ambient air temperature at 10 °C. In 1980, Granqvist and Hjortsberg produced a surface for efficient radiative cooling that consisted of 1.0 μm of silicon monoxide on aluminum. They envisaged that refrigeration to 40 K below the ambient appears to be possible under suitable climatic conditions [5]. One year later, they utilized the same infrared selective surface, and performed a practical test of radiative cooling under transparent polyethylene films in a polystyrene box. The test was conducted during clear nights. A cooling power of about 60 W/m^2 was achieved [6]. In 1984, Berdahl demonstrated that magnesium oxide in ceramic foam can be fabricated into a useful selective radiator which cools well below ambient temperature [8]. The MgO radiator cooled to 5 °C below the reference panel. In 1995, Nilsson and Niklasson prepared five different pigment materials, ZnS, ZnSe, TiO_2, ZrO_2 and ZnO. Simulation results showed that only ZnS could promote cooling of a black body radiator in an insulated box at noon under direct sunlight [12]. In 1993, Orel et al. developed an infrared selective radiator. A temperature difference of about 10 °C was obtained between the radiators and ambient air temperature [10]. They also found that the addition of a $BaSO_4$ extender dispersed in the paint increased the cooling performance of the painted radiators. In 2000, Khedari et al. studied the feasibility of cooling by using night radiation under Thailand's hot and humid climate [3]. The experimental results showed that the depression of different surface temperatures was in the range of 1–6 °C below ambient temperature under clear and cloudy skies. The temperature of different surfaces of roof radiators and ambient air was fairly close under rainy skies. Besides, they also found that the thermal emissivity of materials and water condensation on the radiator surface area are the two major factors affecting night radiation cooling. In 2009, Suryawanshi and Lin designed and developed a high-surface-emissivity "molecular fan" coating, consisting of an acrylate resin and carbon-based materials on aluminum panels [16]. The "molecular fan" nano-coating can act as a selective emitter and displayed an enhanced emissivity. The results showed that using 1wt% multi-wall carbon nanotube, the "molecular fan" coating on one side of the aluminum test panel lowered the equilibrium temperature of a heat sink by 17 °C. In 2010, Gentle and Smith demonstrated a mix of two resonant nanoparticles, SiO_2 and SiC [11]. They found that a mixture of SiC and SiO_2 nanoparticles yielded high performance cooling at low cost within a practical cooling rig.

By using photonic structures to selectively reflect and emit photons in different wavelength regimes, a net cooling effect can be achieved if the emission of infrared to outer space, whose radiation background temperature is about 2.7 K, exceeds the absorption of sunlight and environment thermal radiation. In other words, to realize net passive radiative cooling below ambient air temperature, strong reflection of sunlight and strong emission of thermal radiation with a wavelength within the atmospheric infrared window (8–13 microns) must be achieved simultaneously; however, it is extremely difficult to achieve using conventional optical coatings. Recent success in passive radiative cooling is attributed to the adoption of a multilayer photonic structure. By creating a subwavelength photonic structure, the spectral absorption, emission and transmission of photons can be controlled. It has been demonstrated in California (USA) that passive radiative cooling of 4.9 °C below ambient air temperature can be achieved under direct sunlight with a photonic radiative cooler consisting of a silicon substrate and a multilayer photonic structure, which shows a cooling capacity of 40.1 W/m^2 [17]. This promising result again excites the research interest in radiative cooling since passive radiative cooling no longer has to be limited to night operation. However, their design could be further optimized from a heat transfer perspective. It was predicted that the cooling performance can be improved by about four times if the non-radiative heat transfer coefficient is reduced to zero.

According to our knowledge, there is no field investigation of radiative cooling in Hong Kong. This paper is intended to make an initial feasibility study on how effective this technique would be under a sub-tropical sky. One major difference between California (USA) and Hong Kong is the humidity. Harrison [18] reported that the absolute humidity at ground level can strongly influence the radiation cooling effect of TiO_2 white paint. The performance of a photonic radiative cooler is also affected by humidity. Overall, this study aims to experimentally investigate the passive radiative cooler described in Ref. [17] with different thermal designs (i.e. vacuum and non-vacuum configurations) and test its cooling performance in the hot and humid environment of Hong Kong. It should be noted that the non-vacuum design of the passive radiative cooler indeed is the cooler described in Ref. [17], while the vacuum design configuration of the passive radiative cooler is our proposed design. Vacuum is a common method to eliminate conductive and convective heat transfer to the surrounding environment. This method is widely used in vacuum bottles, evacuated tube solar collectors, vacuum insulation panels, etc. The effect of different sky conditions on the cooling performance of the passive radiative cooler, such as clear, cloudy and partly cloudy, are studied. Lastly, some recommendations on how to further enhance the cooling performance of the passive radiative cooler are also addressed.

2. Experimental setup

As California's weather is totally different from Hong Kong's, it is necessary to assemble the same setup in Hong Kong so that a fair comparison can be made. Most importantly, the effect due to different weather conditions can be eliminated. Based on the design proposed in Ref. [17], an identical prototype was built as shown in Fig. 1. It should be noted that the passive radiative coolers used in this study and in Ref. [17] were all built by the same company (LGA THIN FILMSTM, Inc. Santa Clara, CA 95051) located in California (USA). Briefly, the photonic radiative cooler consists of seven alternate layers of hafnium dioxide (HfO_2) and silicon dioxide (SiO_2) of varying thicknesses, on top of 200 nm of silver (Ag), which are all deposited on a 200 mm silicon wafer [17]. The cooler can reflect 97% of incident sunlight, while at the same time, strongly and selectively emitting the thermal radiation heat in the atmospheric transparent window (8–13 μm). As a result, a cooling effect can be produced by the passive radiative cooler. Please refer to Ref. [17] for details about the exact thickness of each layer as well as the overall thermal design configuration of the passive radiative cooler.

Based on the simulation result published by Raman et al. [17], the passive radiative cooler can reduce the ambient air temperature by about 20 °C if both conductive and convective heat losses are negligible. In their experimental setup, the radiative cooler was suspended in a relatively well-sealed air pocket. However, it should be noted that no matter how well the air pocket is sealed, conductive and convective heat losses still exist. In order to