Performance Assessment of a Promising Radiative Cooler for Cool Roofs via Simulation

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Abstract. Radiative cooling is an age-old cooling practice that advantages in decreasing cooling energy requirements without power input. To apply this technology to the energy-efficient building industry, radiative coolers’ performances should be assessed in advance. Using a simulation approach, the work in this study was to justify whether a promising radiative cooler would lead to the cooling energy reduction on a modelled roof in Beijing. The promising radiative cooler was reported to have the potential to achieve a temperature of 9.9 degrees Celsius below ambient temperature, which is a significant improvement over the results found in previous literature. Simulation outputs show that this material can lead to the cooling energy reduction on a modelled, 1000 square meters roof constructed in Beijing. This also implies that the promising cooler have a large potential of energy savings if they could be applied in Beijing.

1. Introduction

Building energy consumption accounts for approximately 40% of the total energy consumption of the world, where a large amount of energy is used for indoor thermal management via conventional heating, ventilating and air-conditioning (HVAC) systems [1]. Therefore, as a passive, effective, and renewable way of decreasing cooling energy requirements without power input, radiative cooling has attracted considerable attention in the field of energy-efficient buildings [2]. And one of the energy-saving applications is called ‘cool roofs’, which render the external surface colder by reducing the cooling demands of buildings and easing the urban heat island phenomenon for pumping the heat to outer space [3, 4]. More encouragingly, a potential long-term benefit of applying such technology can be achieved through balancing the total heat fluxes into and away from the entire Earth such that warming would cease and finally climate change could be mitigated [5].

Nowadays, radiative cooling system is considered an essential part of cool roof. Consequently, the building materials and the optimization process of the radiative cooler can be of great significance. Generally, building materials of a radiative cooler can be divided into four categories: (1) Natural radiators, (2) Film-based radiators, (3) Nanoparticle-based radiators and (4) Photonic radiators [2]. Among these different material structures, the photonic approach advantage in having the ability of facilitating the modification of the spectral radiative properties of the radiator by proper periodic structuring and has been rapidly developed for radiative cooling, especially for sub-ambient diurnal radiative cooling. The aim of this study is to demonstrate the simulation and relevant performance of an
optimized photonic radiative cooler assumed to be applied in Beijing based on the model using Taguchi's method [6].

2. Method

2.1. Fundamental Principles of Radiative Cooling

The energy balance process of a radiator in radiative cooling process is illustrated in Fig. 1, where $q_{\text{rad}}$ denotes the energy radiated flux, $q_{\text{sun}}$ is the solar energy absorbed flux, $q_{\text{sky}}$ refers to the atmospheric radiative energy absorbed flux, and $q_{\text{loss}}$ represents the intrinsic cooling loss flux. [2]

![Figure 1. Energy fluxes of a radiator [2].](image)

According to energy balance theory, the net radiative cooling power of the radiator is the comprehensive manifestation of the four preceding energy fluxes mentioned and can be expressed as follows [7]:

$$q_{\text{net-cooling}}(T) = q_{\text{rad}}(T) - q_{\text{sky}}(T_{\text{sky}}) - q_{\text{sun}} - q_{\text{loss}}$$  \hspace{1cm} (1)$$

Where $q_{\text{net-cooling}}$ is the net radiative cooling power of the radiator, W/m$^2$; and $T$ denotes the absolute temperature of the radiator, K. The related theories and calculations of different energy fluxes expressed in Eq. (1) are mostly summarized and analyzed in Zhao, B.’s (2019) review [2]. There are a variety of models built for each specific situation, however, only a most widely accepted mathematical model is shown below in Eq. (1-5) [7], on which the following analysis is based, and a detailed nomenclature can be found in the Simulation section.

$$q_{\text{rad}}(T) = \int d\Omega \cos \theta \int_0^\infty d\lambda I_{BB}(T, \lambda) \varepsilon(\lambda, \theta)$$  \hspace{1cm} (2)$$

$$q_{\text{sky}}(T_{\text{sky}}) = \int d\Omega \cos \theta \int_0^\infty d\lambda I_{BB}(T_{\text{sky}}, \lambda) \varepsilon(\lambda, \theta) \varepsilon_{\text{sky}}(\lambda, \theta)$$  \hspace{1cm} (3)$$

$$q_{\text{sun}} = \int_0^\infty d\lambda \varepsilon(\lambda, \theta_{\text{sun}}) I_{AM1.5}(\lambda)$$  \hspace{1cm} (4)$$

$$q_{\text{loss}} = h_c(T_{\text{sky}} - T)$$  \hspace{1cm} (5)$$

2.2. Material and structure of the radiator

The design process of photonic radiative coolers involves engineering the optical spectrum of the device using available optical materials [6]. Multilayer thin film structures on top of a reflective substrate can be designed to have a specific emission spectrum [8–11]. Such structures are simple and relatively inexpensive to fabricate [6]. For these reasons, Mohammad Asif Zaman (2019) selected a multilayer thin film stack to design his passive radiative cooler. A schematic diagram of the structure is shown in Fig. 2 and its corresponding optimized parameters (by Taguchi’s method) are summarized in Table 1[6].
Passive cooling devices require optimizing the spectrum in both solar and thermal wavelength regimes, see in Fig. 3.(a) [2]. The performance of the photonic cooler with the optimized parameters are shown in Fig. 3.(b). It suggests that the optimized spectrum matches closely to the target spectrum. Suppression of the spectrum in both the solar spectrum and the ozone absorption region (8-13μm) is achieved.

**Figure 2.** Geometry of the photonic radiative cooler [6].

**Table 1.** Optimized parameters [6].

| layer | Material | Thickness (μm) |
|-------|----------|----------------|
| 1     | MgF₂     | 2.903          |
| 2     | TiO₂     | 1.764          |
| 3     | MgF₂     | 0.578          |
| 4     | MgF₂     | 1.633          |
| 5     | SiN      | 0.392          |
| 6     | SiO₂     | 2.370          |
| 7     | MgF₂     | 2.036          |

**Figure 3.** (a) Radiative properties of different radiators, with AM 1.5 solar spectrum and a typical atmospheric window plotted; Emitter A is a narrowband-ideal radiator with high emissivity only within the sky atmospheric window, whereas Emitter B is a broadband-ideal radiator with high emissivity in the entire mid-infrared band (i.e., over 4μm) [2]. (b) Both the normal emissivity, and the average emissivity (averaged over the incident angles) of the device are shown. The target spectrum, AM1.5 solar spectrum and the atmospheric transmission spectrum are also shown in the figure [6].
Moreover, the optimized photonic cooler achieves a temperature of 9.9°C below ambient temperature which is a significant improvement over the results found in the literature (e.g. 6.2°C below ambient for the design presented in Raman’s (2014) study[7]).

3. Simulation & Results

Considering all the outstanding features described above, the simulation performed in this section is thoroughly based on the optimized multilayer material. The primary objective of the following simulation is to justify that the promising material can lead to the cooling energy reduction on a roof with certain areas constructed in Beijing.

From the model proposed by Zaman (2019), which integrated the Taguchi’s Method with the model introduced in the Fundamental Principles’ section, the $q_{\text{net-cooling}}$ is correlated with several parameters as summarized in Eq. (6) [6]. And the nomenclature for Eq. (6) is listed in Table 2.

$$q_{\text{net-cooling}} \propto \left( T, T_{\text{Ambient}}, \varepsilon(\lambda, \theta, d, n(\lambda)), I_{BB}(\lambda, T, h, c, k_B), h_c, I_{AM1.5}(\lambda) \right)$$

**Table 2.** Nomenclature for Eq. (6) [6].

| $q_{\text{net-cooling}}$ | The net radiative cooling power |
|--------------------------|-------------------------------|
| $T$                      | Radiative cooler temperature  |
| $T_{\text{Ambient}}$     | Ambient temperature           |
| $\varepsilon$            | The emissivity of a multilayer thin film structure |
| $\lambda$                | Wavelength range              |
| $\theta$                 | Incidence angle               |
| $d$                      | The thickness of the layers of the multilayer structure |
| $n$                      | The refractive index of each layer |
| $I_{BB}$                 | The emission intensity spectrum of a blackbody given by Planck’s law |
| $h$                      | The Plank’s constant          |
| $c$                      | The speed of light            |
| $k_B$                    | The Boltzmann constant        |
| $h_c$                    | The non-radiative heat coefficient |
| $I_{AM1.5}$              | The AM1.5 solar spectrum      |

The simulation is based on the weather data collected from Beijing International Airport, where the summers are long, warm, humid, wet, and partly cloudy and the winters are freezing, dry, and mostly clear. Over the course of the year, the temperature typically varies from 17°F to 88°F and is rarely below 9°F or above 96°F. The temperature and solar energy data can be found at Weather Spark, and they are also illustrated in Fig. 4 and Fig. 5 below[12].

![Figure 4](image)

**Figure 4.** (a) The daily average high (red line) and low (blue line) temperature, and the thin dotted lines are the corresponding average perceived temperatures [12]. (b) The average ambient temperature calculated from (a).
Figure 5. The average daily shortwave solar energy reaching the ground per square meter (Orange line) [12].

Solar irradiance can be calculated from the average daily solar energy based on the detailed measuring method described in the original resource. The average output is a little lower than the values reported in Raman’s (2014) study [7]. To simplify the problem, we decided to use the assumption proposed in Zaman’s (2019) study [6], in which the irradiance was 1000 W/m² when the ambient temperature was assumed to be 300K. Besides, the AM1.5 solar spectrum and the atmospheric transmission data are illustrated in Fig. 6 [6].

Figure 6. The AM1.5 solar spectrum and the atmospheric transmission data.

In Eq. (6), several parameters are constants already, like the Boltzmann constant, the Planck’s constant and the speed of light. Several other parameters hardly show differences between Stanford and Beijing, therefore we decided to treat them as the same. As for \( h_c \), we set a series of values: 0, 2, 6.9, 25, 100 Wm\(^{-2}\)K\(^{-1}\) to see how this material will react under idealistic situation, normal situations and the non-radiative process. Basically, we were following the work previous groups have done, however, Fig. 7 provides a better comparison of all these circumstances mentioned above using the code and methods provided in Zaman’s (2019) study [6].

Figure 7. Cooling power as a function of temperature difference at different \( h_c \) values. \( T_{amb}=300K \) is used for all the plots.
Considering that for planar structures experiencing natural convection in air, the convection heat transfer coefficient ranges from 2 to 25 Wm\(^{-2}\)K\(^{-1}\) [13], and again, just to make matters easier, we referred to Raman’s (2014) similar simulation result, and proceeded our study with the \(h_c\) equaled 6.9 Wm\(^{-2}\)K\(^{-1}\).

From Eq.(6), the temperature of the radiative cooler can be calculated when the system achieved steady-state and the results are shown in Fig. 8, together with the input ambient temperature collected in Beijing. From the picture, it can be noted that each device’s temperature is lower than the ambient temperature in the corresponding month suggesting that this proposed material have the potential of energy saving if being applied in Beijing. And in Fig. 9, it can be seen that the temperature difference ranges from 5.5 to 9.9 degrees. What’s more, the value of \(P_{\text{amb}}\), which has a negative correlation with the temperature difference when the system achieved the steady-state is recorded in Fig. 9.

![Figure 8. The ambient temperature and the calculated radiative cooler temperature.](image)

![Figure 9. \(P_{\text{amb}}\) and temperature differences in each month calculated at steady-state.](image)

With relevant data obtained for this study, working performances of the radiative cooler can further be analyzed in six selected months with relatively high desire of the cooling demand (see in Figure 10). Assuming the temperature difference of the photonic radiative cooler can be engineered to be a constant, we took an assumption of it equaled 7 degrees. Based on this assumption, energy saving achieved by this promising radiative cooler can be calculated if it is applied on a modelled 1000m\(^2\) roof from April to September (see in Fig. 11).
Figure 10. Performance lines of the radiative cooler working in months arranging from April to September

Figure 11. Energy savings for the material assumed to be applied on a modelled, 1000m² roof from April to September.

4. Discussion

Fan and Raman (2017) predicted that if the SkyCool system was used in Las Vegas, where the weather is hot and dry, the system could reduce the building’s cooling power consumption by 21% in summer [14]. Also, Yin and Yang (2019) proposed that if their radiation cooling materials could be integrated with water coolers in commercial buildings in Phoenix, Miami and Houston, it would reduce summer cooling electricity consumption by 32-45% [15]. Moreover, Liangbing Hu predicted that if super-cold wood materials could be commercialized and applied, this material would save 20-35% of cooling energy in 16 cities in the United States [16]. Rough calculations from Munday’s (2019) showed that the current rising temperature could be balanced by covering 1-2% of the earth’s surface with existing radiation cooling materials, and these materials could generate about 100 W/m² of cooling energy during the day [5].

Furthermore, the use of radiation cooling materials for indoor cooling can reduce the impact of air conditioner on human health. Staying in a comfortable air-conditioned environment for a long time will not only weaken the body’s temperature regulation ability, but also weaken other physiological functions of the body, such as water and salt metabolism [17]. Although the air conditioner has the
function of constant temperature and humidity as well as providing clean air, people still often feel dizzy, 
easy to fatigue, lethargy, lack of energy and lack of comfort [17].

Because the development of radiation cooling materials is still in its initial stage, there are some 
limits in their application. Firstly, the radiation cooling materials have the best cooling effect in a dry 
and sunny climate, however, when the weather is cloudy or humid, the water vapor present in the air 
will capture infrared radiation, which would cause the reduction of the heat reflection ability of the 
material [18].

Secondly, radiation cooling systems may increase heating costs in winter [19]. Many people want to 
solve this problem from the structure of the material and encouragingly, the team led by Professor Jiaxi 
Cui (2020) reported a conversion strategy to realize energy-saving heating in winter and cooling in 
summer by combining solar heating with solar reflection and radiation cooling [20]. This strategy is 
based on a dynamic porous silicon film, which alternates between a transparent solid-state used for solar 
heating and a highly porous state used for solar reflection and radiation cooling [20].

Lastly, radiation cooling materials can only achieve ultra-cooling when they can send radiation 
directly to a cold radiator in the outer space; while, objects in an urban environment like buildings and 
people will get in the way, absorbing heat and re-radiating it to the air [18]. Qiaoqiang Gan and Zhongfu 
Yu hoped to double the effect of the radiation cooling material by aligning the membrane perpendicular 
to the roof so that the infrared ray could escape from both surfaces; however, this would require adding 
materials around the film that would reflect the infrared ray into the sky [21].

5. Conclusion
In this study we justified that the promising optimized multilayer photonic radiative cooling material 
proposed by Mohammad Asif Zaman (2019) can lead to the cooling energy reduction on a supposed 
1000 square meters roof constructed in Beijing through performing a simulation based on several 
idealistic assumptions. The result helps confirm that more energy is saved in summer months where 
there is greater cooling demand; it also implies that radiative cooling materials have a large potential of 
energy saving in the field of energy-efficient buildings.

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