Study on the cooling energy saving potential of a novel radiative cooling paints in building application

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Abstract. Passive radiative cooling technology has attracted much attention for its ability to obtain "free" cooling by heat exchange between objects on earth and outer space through atmosphere window. However, most of the existing radiative cooling materials are prepared in the form of thin films, which limits the application of radiative cooling in building since the films are lacking in scalability and the various building shapes. In this paper, we prepared a radiative cooling paint (RCP) with acrylic resin as the substrate, and mixed with polymethylpentene (TPX), and silicon dioxide (SiO\textsubscript{2}). The emissivity of 0.87 and reflectively of 0.92 is achieved in atmosphere window (i.e., 8-13 µm) and solar spectrum (i.e., 0.2-2.5 µm), respectively. To further indicate the cooling potential of the proposed RCP for its building applications, a two-floor single-family house is modeled using EnergyPlus. The cooling energy saving potential of the prepared RCP for applying on different surfaces of the building envelope is analyzed, and the influence factors for the application of RCP is discussed in detail. The results show that a significantly cooling energy saving can be achieved for the buildings painted with the proposed RCP on all surfaces (i.e., roofs and walls) in which the annual cooling energy consumption can be decreased by 15.8-31.2% comparing to the building with typical roofs and walls located at all five climate zones in China.

1 introduction

Building energy consumption accounts for around 40% of the total energy consumption, and 45% of the building energy is consumed by the air-conditioning systems [1]. As a passive cooling technology, radiative cooling can mitigate heat from the objects on earth to outer space through atmospheric windows, which can not only reduce fossil energy consumption, but can also decrease the effects of global warming [2]. Although radiative cooling is widely existing in nature, the cooling capacity is insufficient for the natural materials [3].

With the emergence of artificial materials, the cooling capacity of radiative cooling materials has been improved significantly. The diurnal radiative cooling is first achieved by Raman et al. [4] with their proposed planar photonic crystal consisting of seven alternating layers of HfO\textsubscript{2} and SiO\textsubscript{2}, in which the emissivity and reflectivity are 0.92 and 0.97. Their results showed that the surface of planar photonic crystal can be cooled by 5°C lower than the ambient temperature under the solar irradiance of 850 W/m\textsuperscript{2}. The research on the radiative cooling has increased significantly after the breakthrough of diurnal radiative cooling. And radiative cooling materials have covered films [5], paints [6], woods [7], and fabrics [8]. Especially for radiative cooling films, there are a larger number of studies have been conducted [9-11].

Compared to the radiative cooling film (RCF), the radiative cooling paint (RCP) is more feasibility for the application in buildings accounting for various shapes of buildings. The waterborne PTFE monomeric of fluorocarbon paint was adopted by Mastrapostoli et al. [12] as cool roof of an industrial building. Their study showed that energy consumption for cooling and heating can be reduced by 73% and 5%, respectively. The cooling performance of a super cool roof based on the porous painting [P(VdF-HFP)HP] was investigated by Baniassad et al [13]. The results showed that the total energy consumptions can be reduced by 4-19% for the commercial building and 28% for the residential building by applying the super cool roof. Although the existing publications demonstrate the significantly cooling energy-saving potential of RCP for building applications, most of them are derived from roof painted (cool roof). There are few studies focused on other surfaces of the buildings.

In this study, we prepared a novel RCP that can be applied to various locations of the building very simply. And then the cooling energy saving potential is analyzed for the building painted RCP in different ways. Finally, the effect of climate on the cooling performance of RCP is also discussed.

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2 Methods

2.1 Preparation of radiative cooling paints

The acrylic resin, TPX (poly(methylpentene)), and SiO2 are adopted for the preparation of RCP. The process of preparation is given in Figure 1. The emissivity (8-13 μm) and reflectivity (0.2-2.5 μm) of the proposed RCP are 0.87 and 0.92, which can also be found in Figure 2. The RCP can be painted on the surface of wall and/or roof directly. The cost for the application of RCP is quite low if the labor cost is not considered. According to the retail price (Longchuang New Material Co.Ltd, WenJia Chem Co.Ltd, Shenzhen Xinfu Plastic Co.Ltd), the estimated price of RCP is approximately $1.76 per square meter.

The RCP can be painted on the original roof (shingle) and/or wall (stucco) to provide the cooling energy to the building, and an air-conditioning is also employed in this model to supply the supplemental cooling so that the room temperature can satisfy the requirement in Table 1.

Table 1. Details of the building model.

| Items                   | Parameter | Items       | Parameter         |
|-------------------------|-----------|-------------|-------------------|
| Floor area              | 204 m²    | Roof area   | 118 m²            |
| Window-wall ratio       | 10%       | Indoor air temperature setpoint  |
|                         |           | Cooling: 24°C | Heating: 22°C     |
| Thermal conductivity    | Wall: 1.39 W/m-k | Exterior material | Wall: Stucco     |
|                         | Roof: 0.19 W/m-k | Roof: Asphalt shingle |
| Solar absorptance       | Wall: 0.75 | Thermal absorptance | Roof: 0.25     |
|                         | Wall: 0.1 |                         | Wall: 0.9       |

Fig. 1. Process of preparation for RCP.

Fig. 2. Emissivity and reflectivity of RCP.

2.2 Description of the model

To further indicate the cooling potential of the proposed RCP, a two-floor single-family house model originated from [14] is used in this study (Figure 3). The model is built in EnergyPlus, and the dimension of the single-family house is 12.18 m × 9.16 m × 5.18 m (length × width × height), and other details of the model are given in Table 1.

The building at Nanjing, China is taken as an example to compare the cooling potential of RCP painted by different ways. There are three ways should be considered, including paint on the roof (RCProof), painted on the wall (RCPwall), and painted on the roof and wall (RCProof+wall). Furthermore, five cities, including Guangzhou (hot summer and warm winter zone), Kunming (moderate zone), Xi'an (cold zone), Harbin (severe cold zone), and Nanjing (hot summer and cold winter zone) are selected to analyze the cooling energy-saving potential of RCP painted building at different climate zones in China. The weather data adopted in this study are all from [15].

2.3 Heat transfer calculation

Take the roof painted with RCP as an example, the process of heat transfer on the surface of RCP is given in Figure 4.
From Figure 4, the net radiative cooling power can be expressed as [16],

\[ q_{\text{rs}} = q_{\text{rad}} - q_{\text{conv}} - q_{\text{sol}} - q_{\text{cond}} \tag{1} \]

where \( q_{\text{rs}} \) is the net radiative cooling power of RCP; \( q_{\text{rad}} \) is the radiative heat transfer between RCP and outer space; \( q_{\text{conv}} \) is the convective heat transfer between the surface of RCP and ambient; \( q_{\text{sol}} \) is the solar absorption of RCP; and \( q_{\text{cond}} \) is the heat transfer from RCP to room.

In equation (1), the \( q_{\text{rad}}, q_{\text{conv}}, q_{\text{sol}}, \) and \( q_{\text{cond}} \) can be calculated by [17, 18],

\[ q_{\text{rad}} = \sigma e_{\text{surf}} (T_{\text{surf}}^4 - T_{\text{sky}}^4) \tag{2} \]

\[ q_{\text{conv}} = h_e (T_{\text{surf}} - T_{\text{amb}}) \tag{3} \]

\[ q_{\text{sol}} = -\lambda (T_{\text{surf}} - T_{\text{amb}}) \tag{4} \]

\[ q_{\text{cond}} = \frac{\Delta T_{\text{surf}}}{\delta} \tag{5} \]

where \( \sigma \) is the Stefan-Boltzmann constant, \( 5.67 \times 10^{-8} \) \(^\text{W m}^{-2} \text{K}^{-4}\); \( e_{\text{surf}} \) is the emissivity of RCP; \( T_{\text{surf}} \) is the surface temperature of RCP; \( T_{\text{sky}} \) is the effective sky temperature; \( h_e \) is the convective heat transfer coefficient on the surface of RCP; \( T_{\text{amb}} \) is the ambient temperature; \( \lambda \) is the coefficient of solar absorption; \( I_{\text{sol}} \) is the incident solar irradiance; \( \Delta T \) is the temperature difference between the surface of RCP and bottom of roof; \( \lambda_{\text{surf}} \) is the thermal conductivity of roof; and \( \delta \) is the thickness of roof.

In equation (2), \( T_{\text{sky}} \) can be estimated by [19],

\[ T_{\text{sky}} = T_{\text{sky}}^{1/4} T_{\text{amb}}^{3/4} \tag{6} \]

\[ \varepsilon_{\text{sky}} = 0.711 + 0.56 \left( \frac{T_d}{100} \right) + 0.711 \left( \frac{T_d}{100} \right)^2 \tag{7} \]

where \( e_{\text{sky}} \) is the sky emissivity; and \( T_d \) is the ambient dewpoint temperature.

In equation (3), \( h_e \) can be calculated by [20],

\[ h_e = 8.3 + 2.5 V_{\text{wind}} \tag{8} \]

where \( V_{\text{wind}} \) is the local wind speed.

3 Result and discussion

3.1 Annual electricity consumption

The annual cooling electricity consumption of the building with RCP in Nanjing, China is given in Figure 5. As shown in Figure 5, RCP shows a great cooling energy-saving potential. By comparing the building with shingle roof and stucco wall (RCP\textsubscript{non}), the annual cooling electricity can be decreased by 228 kWh of RCP\textsubscript{roof}, 498 kWh of RCP\textsubscript{wall}, and 716 kWh of RCP\textsubscript{roof+wall}, resulting a reduction of 5%, 11%, and 15.8%, respectively. Especially for the RCP\textsubscript{roof+wall}, approximate 11.3% of annual cooling electricity can be reduced by comparing with the most commonly configuration of cool roof (RCP\textsubscript{roof}).

Fig. 5. Annual cooling electricity consumption of the building in Nanjing.

3.2 Monthly electricity consumption

The monthly cooling electricity consumption for the building application of RCP\textsubscript{roof+wall} in Nanjing, China is also given in Figure 6. It can be found in Figure 6, more cooling electricity-saving can be achieved in the cooling season (June to September).

Fig. 6. Monthly cooling electricity consumption of the building in Nanjing.

By comparing with the building application of RCP\textsubscript{non}, the cooling electricity consumption can be decreased by 110.3 kWh in June, 128.5 kWh in July, 133.9 kWh in August, and 98.6 kWh in September. It also means that 18.1% of cooling electricity on average can be saved during June to September by RCP\textsubscript{roof+wall} of the building. However, the cooling energy-saving is relatively lower in the heating season. During November
to January, only 6.3% (16 kW per month) of cooling energy consumption on average can be achieved. Therefore, RCP is more suitable for the climate zone that need cooling all year round.

### 3.3 Energy-saving of RCP in different climates

As mentioned in Section 2.2, five cities are selected to comparing the cooling energy-saving potential for the building with RCP in different climate zones. The annual cooling electricity consumption for these five cities are presented in Figure 7.

![Figure 7](https://example.com/figure7.png)

Fig. 7. Annual cooling electricity consumptions of the buildings located at different climate zones.

By comparing with the building application of RCP non, the annual cooling electricity consumption can be decreased by 1073.6 kWh in Guangzhou, 807.5 kWh in Kunming, 716.6 kWh in Nanjing, 771 kWh in Xi'an, and 731.8 kWh in Harbin, resulting a reduction of 19.2%, 31.2%, 15.8%, 18%, and 18.7% for above five cities. Although the percentage of cooling electricity-saving for the building in Kunming is high than that in Guangzhou, the decreases of the cooling electricity is lower than that in Guangzhou. It is because that Guangzhou is located at hot summer and warm winter zone which has more cooling demand. The relative higher cooling electricity-saving potential in Guangzhou and Kunming means that it is more suitable for the application of RCP in hot summer and warm winter zone and moderate zone.

### 4 Conclusions

This paper analyzes the cooling energy saving potential of our proposed RCP based on the EnergyPlus. The cooling electricity consumption are compared for the building painted with RCP in three different ways. And then the cooling electricity-saving potential for the building with RCProof+wall located at all five climate zones are discussed. The main conclusions are as follows:

- More cooling electricity can be reduced for the building with RCProof+wall. Compared to the building with RCPnon, RCProof, and RCPwall, the cooling electricity can be decreased by 15.8%, 11.3%, and 5.4% in hot summer and cold winter zone, respectively.
- 15.8%-31.2% of annual cooling electricity-saving can be achieved for buildings painted with RCP on the roof and wall in all five climate zones of China.

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