Deployment Integration Strategy for Daytime Radiative Cooling Materials: A Comparative Numerical Analysis of Roof Cooling and Water-Cooling Panels

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Abstract. Daytime radiative cooling has emerged as a promising solution for continuous passive cooling. While significant progress has been made in material developments, questions persist regarding the potential large-scale deployment of this technology. Among the potential applications, two predominant uses of daytime radiative cooling materials are under study: passive roof cooling and water-cooling panels. In the present study, a numerical assessment to compare the benefits of both integration schemes for passive daytime radiative cooling materials is conducted. These findings suggest adjusted approaches based on climatic considerations for the optimal deployment of daytime radiative cooling technologies worldwide.

1 Introduction

Recently, considerable number of passive daytime radiative cooling (PDRC) materials have been developed with promising spectral properties. However, despite their appealing performance, existing PDRC materials are still far from large-scale deployment in cooling systems. The integration of PDRC materials in building space cooling applications presents several challenges beyond the material performance itself, such as complexity of cooling configurations, variations in cooling load profiles, impact of weather conditions on material performance, and considerations related to cost and payback [1].

Among the potential applications, two predominant uses of PDRC materials stand out as noteworthy: passive roof cooling and water-cooling panels [2]. Passive roof cooling involves in depositing PDRC material on the roof to passively cool the building by reflecting incoming solar rays and emitting thermal radiation. The second application uses outdoor panels with PDRC surfaces to passively cool water, which can be used to sub-cool the cooling refrigerant below the condensation temperature, thereby improving the system's energy efficiency.

In the present study, a numerical assessment is conducted to compare the benefits of these two application schemes. The aim of this work is to identify optimal integration strategies for PDRC materials in building space cooling, considering factors such as climate, location, and building specifications.

2 Model Description

To quantify the potential of each integration scheme, various components of the global system are modelled:

- Building model to assess cooling load profile.
- Air conditioner (AC) model for cold production and electrical consumption.
- PDRC materials' and panels' performance.
- Dynamic building air temperature model to simulate the control behaviour and cycling performance of the AC.

2.1 Building and Air Conditioning Models

To compute the building cooling load, a heat balance equation for a 8×4×3 m^3 single-room building is applied [3]. The heat transfer to the room are from ventilation, convection and conduction within each wall, solar radiation absorbed by each wall and internal heat generation. These calculations determine the heat gains and losses required to achieve the set-point temperature within the room. A dynamic model of the room air temperature is presented in Equation (1).

$$\mathbf{C} \times \frac{\mathrm{d}\mathbf{T}}{\mathrm{dt}} = \mathbf{A} \times \mathbf{T} + \mathbf{E} \times \mathbf{S} \quad (1)$$

C is the diagonal matrix of heat capacities, **T** is the discretized temperature vector, **A** is the square matrix containing the heat transfer coefficient between the nodes, **E** is the matrix containing the heat transfer coefficient with the external solicitations, and **S** is the vector of external solicitations. Exponential matrix explicit resolution scheme with a fixed time step is used to solve the system differential equation [4].

AC with fixed-speed compressor is modeled. The refrigerant has a constant volumetric flow rate determined by the size of the compressor. Energy balance and pinch

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analysis are used on both the condenser and the evaporator to determine the pressure stages [5].

2.2 Radiative Sky Cooling Panels Model

The net radiative cooling power q_{PDRC} generated at the surface of the PDRC panel is given by Equation (2).

$$q_{PDRC} = q_{rad} - q_{atm} - q_{sun} - q_{parasitic} \qquad (2)$$

q_{rad} is the outgoing radiative power by the surface, q_{atm} is the amount of absorbed atmospheric radiation, q_{sun} is the absorbed solar heat flux and $q_{parasitic}$ represents the parasitic heat gain from the surroundings [6]. Heat transfer equations in steady state are applied to the water inside the panel. Finite volume method is used to determine the profile of water temperature inside the PDRC panel. Cold water produced is used to sub-cool the refrigerant of the AC.

Regarding the optical properties of the materials, PDRC is assumed to have ideal spectral properties as described in [6], with up to 97% solar reflectivity and an ideal selective infrared profile. For the baseline case, the walls are considered to be made of concrete, with 35% solar reflectivity and a thermal conductivity of 1.5 W/m·K, without any added insulation.

3 Results and discussions

Typical Meteorological Year (TMY) data were retrieved from the Copernicus database for four cities, each representing a different climate: Paris (oceanic climate), Dubai (desert climate), Singapore (tropical climate), and Brasília (tropical monsoon climate). The cooling and heating seasons, as well as AC sizing, vary in each city.

3.1 PDRC Passive Roof Cooling

The heat load profile is calculated for each city for a typical roof made of concrete and a roof made of PDRC. Results are presented in Figure 1.

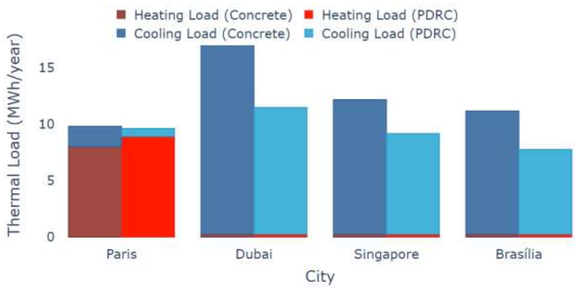

Figure 1. PDRC roof reduces building cooling load.

In temperate-to-cold cities like Paris, placing PDRC on the roof increases the heating load, which offsets the reduction in cooling load observed during the hot season. In contrast, in hotter cities where cooling demand is consistently high, PDRC roof cooling significantly reduces the cooling load, with reductions of 36% in Dubai, 31% in Brasília, and 22% in Singapore.

3.2 Sub-Cooling with PDRC Panels

The AC and dynamic room temperature models are used to calculate the electrical consumption of the cooling device across three scenarios: the baseline case (no PDRC, only concrete), the passive roof cooling case, and the refrigerant sub-cooling case.

The results indicate that electrical savings from the panel sub-cooling integration are lower than those from passive roof cooling, with electrical savings of 15% in Paris, 11% in Dubai, 7% in Singapore, and 8% in Brasília. However, it is crucial to consider the surface area of PDRC material involved. In the case of PDRC active water cooling, only 8 m² (4 panels) are used, whereas the passive roof cooling scenario involves covering 20 m².

Table 1. Annual electricity savings per m² of installed PDRC material for a residential AC.

	Electricity savings per m² of PDRC installed (in kWh_{elec}/m^2.year)	
	PDRC Roof	PDRC Sub-cooling
Paris	6	7
Dubai	132	109
Singapore	48	42
Brasilia	61	45

4 Conclusion and Prospects

Numerical results reveal insights into reducing electricity consumption and enhancing energy efficiency of cooling devices by integrating PDRC materials.

- Integration of PDRC in buildings within temperate and cold cities is challenging due to low cooling demand, low surface area availability, and high investment costs.
- In hot and desert cities, PDRC passive roof cooling is a highly effective solution for reducing the cooling demand of buildings.
- In tropical cities, PDRC water sub-cooling could reduce electricity consumption while requiring less space.

It is important to note that these results cannot be generalized due to the variability in building characteristics (e.g., size, insulation, occupancy) and air conditioning configurations. However, the developed models could be used to frame the optimal deployment of daytime radiative cooling technologies worldwide.

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