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Cooling potential and applications prospects of passive radiative cooling in buildings: The current state-of-the-art

Xing Lu, Peng Xu*, Huilong Wang, Tao Yang, Jin Hou

Department of Mechanical and Energy Engineering, Tongji University, Shanghai 201804, China

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ABSTRACT

The universe can be utilized as a sink for heat pumping by means of passive radiative cooling (PRC). This approach is an age-old cooling practice that has had a renaissance with increasing numbers of research papers over the past two decades. This paper reviews the trends of this technique, as well as advancements in recent years, with an attempt being made to analyze the cooling magnitude and developmental prospects for both diurnal and nocturnal periods. The models and calculations for computing the performances of passive radiative cooling systems are discussed along with the designs and fabrication factors that influence a system's performance. Optimizing strategies that maximize the net cooling power are also presented. The various system configurations that are available to date are summarized to demonstrate the building integration forms of PRC systems. The cooling potentials of different systems are assessed by simulations, and it is shown that the daytime cooling energy density is rather modest, even under the most favorable conditions. The barriers that likely exist to widespread application as well as the scopes for further improvements of PRC are also provided. It is noted that the commercialization of PRC systems is primarily limited by coating material constraints and technique reliability. The advent of a new type of material will be a critical solution to the prevalence of PRC.

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* Correspondence to: Department of Mechanical and Energy Engineering, Tongji University, Room A434, No. 4800 Cao'an Road, Shanghai 201804, China.
E-mail address: xupengwb@gmail.com (P. Xu).

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1. Introduction

Cooling is a high-energy-consuming practice that is embarked upon by modern societies, and it is also a dominant driver for daytime demand peaks and overloaded grids [1]. As a rule of thumb, approximately 40% of primary energy is used in buildings, and the major energy consumption is allocated to conventional HVAC systems [2]. A passive cooling technique that cools with no power input or little power input could therefore make a tremendous difference in energy conservation and emissions reduction. Such strategies do not need to cover all of the cooling loads of a space, but should be able to ease the reliance on conventional systems. Passive radiative cooling (hereinafter PRC) possesses enticing potential for reducing energy use in buildings and is one of the viable alternatives in this regard.

Beyond the earth's atmosphere, the void of space has an extremely low temperature, which is close to absolute zero [3]. Cooling would be a straightforward matter if it were possible to harness the cold darkness of the universe as a heat sink, with the atmosphere interposed between us and this potential cooling source. The semi-transparent nature of the atmosphere is conducive to the imbalance of incoming and outgoing energy and could allow for a sub-ambient cooling phenomenon.

Radiative cooling is a common phenomenon at the earth's surface, and it can be illustrated by processes that abound in nature, such as dew and frost formation on plants. Its application is also extensive over many domains: Dew water collection in remote areas is one of the embodiments [4]; collecting coolness via radiative cooling can boost the efficiency of the power output of turbines or other power thermal systems [5]; and radiatively lowering the operating temperature of a solar cell through sky access is an effective way to enhance the efficiency of the cell [6]. However, in this paper, the synergies of PRC with buildings are the main focus.

The cooling potential of PRC in buildings was first utilized by societies in 400 BCE. Night sky cooling was used in the yakh-chal to produce ice by Persians, despite higher ambient air temperatures [7]. Similar ingenious applications have been used in the desert of Chile and with ice pits in the West Indies [8]. From the mid-20th century, various architectural forms and living practices have utilized radiative cooling effects, and nocturnal radiative cooling of buildings has increasingly attracted considerable research [9]. Exposed sleeping areas in courtyards and on rooftops make it possible to reject heat directly to the sky and simultaneously to obtain the advantages of cool outdoor air temperatures and breezes, as illustrated in Fig. 1 [10]. Special roof systems, including roof ponds and radiative cooling panels, similar to solar flat plate collectors, are also typical examples. However, the use of nocturnal radiative cooling was somehow abandoned later due to product reliability and advances in other technologies that favored more conventional means of cooling, e.g., vapor compression or vapor absorption systems.

Until the past decade or two, passive radiative cooling has seen a renaissance that is chiefly motivated by the depletion of fossil fuels and concerns about the environment, which can be observed from efforts directed at studies on improving the performance and use of the passive radiative cooling concept. Some of these attempts are seen in the optimization of selective surfaces and cover foils to explore possibilities for both diurnal and nocturnal radiative cooling [11].

To the knowledge of the authors, several review papers exist on the passive cooling of buildings in a number of top energy journals [12–17], whereas the existing literature reviews that merely pertain to the subject of radiative cooling in buildings are either limited or incomplete. Ming et al. [18] briefly analyze the physical and technical potential of radiative cooling to combat climate change macroscopically. M. Hanif et al. summarize one of the calculation methods of determining radiative cooling power, and Nwaigwe et al. enumerate experiments and field tests on different night-time PRC systems [19,20].

In this paper, a comprehensive overview of passive radiative cooling in buildings is performed on the basis of previous studies, and it has a twofold significance. First, basic concepts and the development courses of PRC systems are presented by reviewing trends in published articles and applications. Second, the outcome of this paper could be accessible for researchers, students and manufacturers who work in this field by addressing key issues in terms of system configurations and modeling, cooling potentials, material constraints, weather restrictions and cost issues. Section 2 introduces the models for calculating the magnitudes of the resources. In Section 3, the classification of PRC systems and summaries of various system designs and configurations are presented. In Section 4, the cooling potential and applications prospects of PRC systems are concisely analyzed. Finally, salient concluding remarks are outlined in Section 5.

2. Models and calculations

In this section, models and calculations of PRC are detailed as the foundation of assessing the cooling magnitudes of the various systems. The net cooling power for radiative cooling is subject to outgoing radiative power by the emitting structure (P_{sur}), the amount of atmospheric radiation (P_{atm}), and the solar irradiance (P_{sun}) and convection that is absorbed by the structure (P_{cov}). The overall heat balance of a radiative structure is described in Eq. (1) [21,22,54,136] and illustrated in Fig. 2.

$$P_{rad}(T_s) = P_{sur}(T_s) - P_{sky}(T_{amb}) - P_{sun} - P_{conv} \tag{1}$$

where $P_{rad}(T_s)$ represents the net radiative cooling power at the surface temperature T_s. $P_{sur}(T_s)$ is the power that is radiated by the surface at the temperature T_s. $P_{sky}(T_{amb})$ is the incident atmospheric radiative power at the ambient temperature. P_{sun} represents the incident solar power that is absorbed by the surface in the daytime. The convection heat transfer is denoted by P_{conv}.

Each item will be elucidated in the following sections, and the optimum strategies for achieving the maximum overall net power are further discussed in Section 2.4.