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Review

Implementation of Passive Radiative Cooling Technology in Buildings: A Review

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Abstract: Radiative cooling (RC) is attracting more interest from building engineers and architects. Using the sky as the heat sink, a radiative cooling material can be passively cooled by emitting heat to the sky. As a result of the development of material technology, RC research has been revived, with the aim of increasing the materials' cooling power as well as finding reliable ways to utilize it in cooling for buildings. This review identifies some issues in the current implementation of RC technologies in buildings from an architectural point of view. Besides the technical performance of the RC technologies, some architectural aspects, such as integration with architectural features, aesthetic requirements, as well as fully passive implementations of RC, also need to be considered for building application. In addition, performance evaluation of a building-integrated RC system should begin to account for its benefit to the occupant's health and comfort alongside the technical performance. In conclusion, this review on RC implementation in buildings provides a meaningful discussion in regard to the direction of the research.

Keywords: radiative cooling; architectural application; combination; passive design architecture

1. Introduction

Global warming forces buildings to consume more energy for cooling. For buildings in urban areas, they also experience the so-called urban heat island (UHI), and this increases the cooling demand even more in the warm and hot climate region [1]. Some locations that used to maintain their thermal comfort via passive cooling also now need mechanical assistance. The International Energy Agency (IEA) reported that energy consumption for cooling has tripled during the last three decades [2]. Reliance of the energy generation on fossil fuel makes the cooling demand somewhat paradoxical, i.e., by cooling down our buildings, we made the earth even warmer [3]. Thus, passive cooling in buildings plays a crucial role in the environment [4].

Various passive cooling techniques have been developed by researchers and engineers. The general mechanism of passive cooling is actually by dissipating heat from buildings to the environmental heat sink [5]. The most commonly utilized mechanism is convection and evaporation. These two heat transfer mechanisms mainly deal with ambient air or ground as the heat sinks. Nowadays, there is an emerging field of study in which thermal radiation is used as a means of cooling with the sky as the heat sink [6]. This mechanism is not new in nature, e.g., plants experienced this with the effect of dew and frost formation on their leaves [7]. In buildings, radiative cooling (RC) can be applied to building envelopes, especially those that acquire the highest sky view factor (SVF).

Despite their potential, RC techniques have not been widely used in buildings. Challenges of RC application are well defined by researchers. The two most frequently mentioned challenges are technical and cost problems. Technical problems are related to low cooling power, sophisticated material technology to produce the radiator, complicated systems in implementations, durability, and maintenance issues [8]. Cost problems consist of high production cost and high installation cost [9,10].

There is also a problem regarding geographical constraints. Generally, the RC panel is highly dependent on climate and geographical conditions. Factors such as sky condition, wind speed, atmospheric particle, etc. strongly affect the performance of RC panels [5,7,11–13]. RC performs badly in humid conditions. Moreover, a problem also occurs in the form of a mismatch between the cooling demand and the supply. The highest cooling power of an RC panel occurs at night, while building occupants require cooling in the daytime [5,14]. From an architectural point of view, options for design are more crucial. RC panels should be placed on the side that is fully exposed to the sky, which already limits the design option of the building roof, or other smaller sky-facing building components [15]. Moreover, the roof-to-floor area ratio is significantly low for multi-story buildings. This again constraints the design option for architects [9]. Furthermore, structural considerations could also limit the design options [15].

In short, implementing passive RC in buildings does not appear to be beneficial for utility and architectural demand. RC power is not enough for a larger building. Moreover, the technology needs to be more building-integrated [5,7,16]. Many proposals for the implementation of RC in buildings are still in the stage of research and development, and they are mainly about the emitter material or the use of RC to assist active cooling technology [17]. These challenges remain further research topics in the RC field.

Although there are several reviews on RC technologies, and some of their conclusions are cited above, to the authors' best knowledge, only two reviews focused on the applications of RC in buildings. The first paper by Lu et al. [7] elaborates on the cooling power of RC materials, which back in 2016 seemed to be the main barrier for the adoption of RC in buildings. A recent review on a similar topic by Chen et al. [18] in 2020 updated the conditions on RC material explorations, which have been improved since 2016 but still require a real building application, not to mention a large-scale one. Chen et al. [18] suggested that the potential for real RC application in buildings might lie in RC combination with a heating, ventilation, and air conditioning (HVAC) system. Moreover, the two reviews also mentioned that there is a need for study on the economic aspect of many prototype RC systems.

However, one stakeholder that is also important for the application of RC in buildings, i.e., the architects, was excluded in the reviews. Architects should be taken into consideration as they implement RC concepts in their designs [19]. Thus, this review offers to fill in the gap by analyzing the current development of RC technology in buildings from an architectural point of view and proposes some possible research direction of passive RC application in buildings. This review does not only include works that directly implement RC in building, but also looks at some relevant papers on the technological development of RC. The review is arranged in six sections with the main content, besides the introduction and conclusions, describing RC principles, its state-of-the-art application in buildings, the architectural features that are involved in current applications, and an outlook for architectural application of passive RC.

2. Radiative Cooling Principles

All solid surfaces radiate heat in the form of electromagnetic radiation, whose power is proportional to temperature and emissivity, and is distributed across the frequency spectrum. Thus, the term total emissive power is differentiated from spectral emissive power, where the former refers to energy emitted over the entire spectrum, while the latter suggests energy emitted at a specific wavelength interval. The spectral emissive power of an ideal blackbody is governed by Planck's law as stated by Equation (1).

$$E_{\mathrm{B}\lambda}(T,\lambda) = \frac{2\pi h c_0^2}{n^2\lambda^5\left[e^{hc_0/n\lambda kT} - 1\right]} \tag{1}$$

$E_{\mathrm{B}\lambda}(T,\lambda)$ is the spectral emissive power of a blackbody at a certain temperature T for a particular wavelength λ, h is Planck's constant (6.626×10^{-34} J·s), c_0 is light speed in vacuum (2.998×10^8 m/s), n is the refractive index of the medium (1 for vacuum), and k is Boltzmann's constant (1.3807×10^{-23} J·K^{-1}). Figure 1 plots the distribution of blackbody emissive power for some temperatures against the wavelength. It indicates that emissions from different blackbody temperatures peaked at different wavelengths. The maximum wavelength λ_{max}, the wavelength in which a blackbody at a certain temperature T emits the maximum power of radiation, can be calculated from Equation (2), which is obtained from Equation (1). When applied to terrestrial bodies with a temperature around 300 K, Equation (2) gives λ_{max} of 9.6 μm [20].

$$\lambda_{max} = \frac{2898}{T} \quad (2)$$

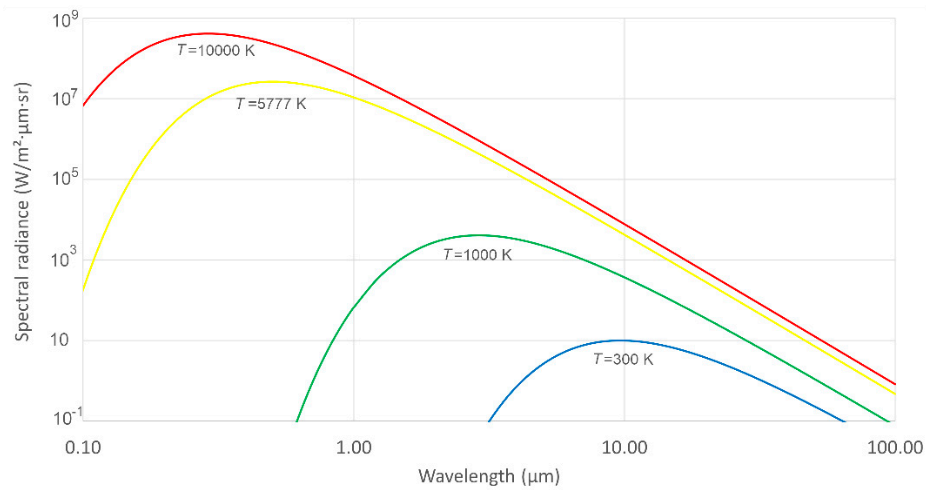


Figure 1. Distribution of spectral emissive power of a blackbody for different temperatures, replotted from SpectralCal [21].

The earth's thermal radiation, which peaks at 9.6 μm, is radiated to outer space through the atmosphere. Fortunately, the earth's atmosphere is relatively transparent for thermal radiation at 8–13 μm, the wavelength in which the λ_{max} of terrestrial radiation peaks. This band is called the atmospheric window. This atmospheric window makes possible the cooling of the earth's surface via radiation in the direction of the sky. Figure 2 superimposes the thermal radiation of a terrestrial body with 300 K temperature on the value of atmospheric transmittance.

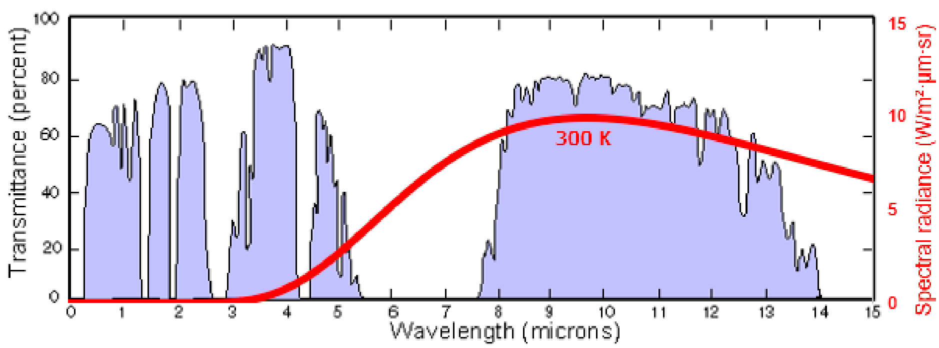


Figure 2. Thermal radiation of average terrestrial temperature (T = 300 K) lies within the atmospheric window band of 8–13 μm [22].

Passive RC techniques utilize this phenomenon. A typical RC panel places the emitter inside a fully insulated frame and protects it from convective heat loss by a transparent cover, usually a polyethylene film, as illustrated by Figure 3. The cooling power (Q_{net}) of a radiative surface is defined as net heat transfer from the surface. A surface exposed to the sky absorbs radiation from the sun (Q_{sun})

and the atmosphere (Q_{atm}) and emits its radiation (Q_{rad}). In addition to the radiative heat emitted or received by the surface, it also gains and loses heat from conduction and convection ($Q_{cond+conv}$). Thus, the energy balance equation of a radiative surface can be written as Equation (3).

$$Q_{net} = Q_{rad}(T,\lambda) - Q_{atm}(T_{amb}) - Q_{sun} \pm Q_{conv+cond} \tag{3}$$

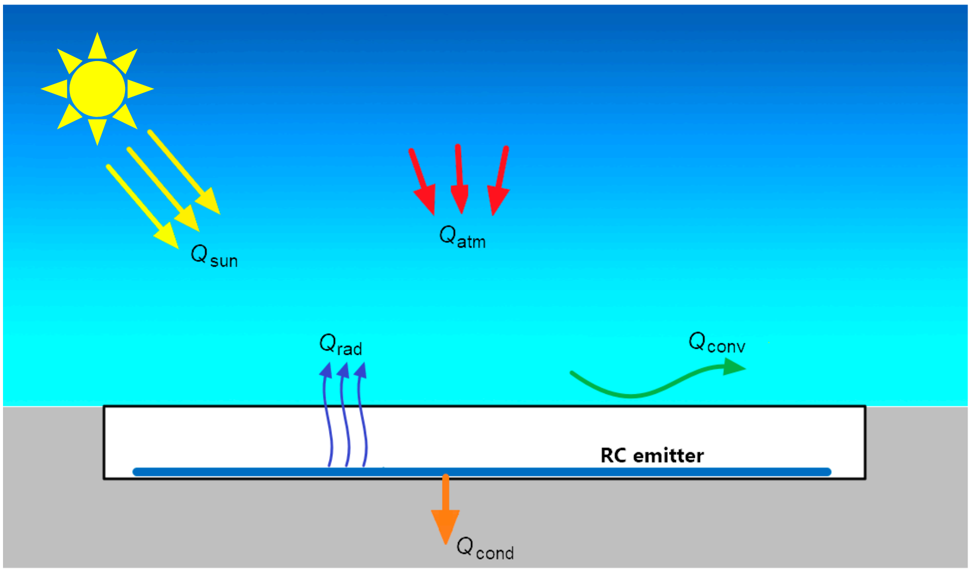


Figure 3. Illustration of typical radiative cooling (RC) panel design and heat transfer on the panel.

Detailed equations for each component of the above equation are summarized by Raman et al. [12]. Q_{rad} is the emissive power of an RC surface with area A at temperature T for the wavelength λ, as shown in Equation (4). The absorbed heat due to incident atmospheric thermal radiation (Q_{atm}) at ambient temperature T_{amb} is given by Equation (5).

$$Q_{rad}(T,\lambda) = A\int d\Omega cos\ \theta \int_0^{\infty} d\lambda E_{B\lambda}(T,\lambda)\ \epsilon(\lambda,\theta) \tag{4}$$

$$Q_{atm}(T_{amb}) = A\int d\Omega cos\ \theta \int_0^{\infty} d\lambda E_{B\lambda}(T,\lambda)\ \epsilon(\lambda,\theta)\ \epsilon_{atm}(\lambda,\theta) \tag{5}$$

where,

$$\int d\Omega = 2\pi \int_0^{\frac{\pi}{2}} d\theta sin\theta \tag{6}$$

In Equations (4) and (5), A represents the area of the emitter, and $\int d\Omega$ denotes angular integral over a hemisphere as shown in Equation (6). Moreover, $E_{B\lambda}(T,\lambda)$ represents the spectral emissive power of blackbody at the emitter's temperature T for the wavelength λ as formulated by Equation (1), whereas $\epsilon(\lambda,\theta)$ is the angle-dependent emissivity of the emitter. For Equation (5), there is an additional emissivity, $\epsilon_{atm}(\lambda,\theta)$, which is the angle-dependent emissivity of the atmosphere.

Further, the absorbed solar radiation is formulated using Kirchoff's radiation law as shown by Equation (7), where $\epsilon(\lambda,\theta_{sun})$ is the emissivity of the emitter at the angle of the sun's position (θ_{sun}). In Equation (7), $I_{AM\,1.5}$ is solar intensity using AM 1.5 spectra. Conduction and convection heat transfer $Q_{cond+conv}(T,T_{amb})$ between the absorber/emitter with the surroundings are also considered in Equation (8), where h_c is heat transfer coefficient, T_{amb} is ambient temperature, and $T_{emitter}$ is the surface temperature of the RC emitter.

$$Q_{sun} = A \int_0^\infty d\lambda \epsilon(\lambda, \theta_{sun})\, I_{AM\ 1.5}(\lambda) \tag{7}$$

$$Q_{cond+conv}(T, T_{amb}) = A\, h_c(T_{amb} - T_{emitter}) \tag{8}$$

From the mathematical model of a typical RC emitter as shown above, factors for a successful RC emitter can be derived. Firstly, the RC emitter needs to be properly insulated from conduction and protected from unwanted convective loss. Secondly, the emitter must have high emissive power in the atmospheric window band. This also means the convection cover needs to be transparent in the same band to transmit the thermal radiation from the emitter. Thirdly, the emitter needs to reflect as much as possible the incident solar radiation to work in the daytime. Another important factor is the atmospheric or sky condition, i.e., a humid atmosphere limits the transparency of the atmospheric window. In other words, a clear sky is more beneficial to the RC emitter than an overcast sky.

3. Research on the Application of Radiative Cooling in Buildings

Attempts to utilize RC in buildings can be traced back to the 1970s when Bartoli et al. [23] and Harrison and Walton [24] conducted experiments using two similar RC emitter designs with different materials, namely TEDLAR (a polyvinyl fluoride film) and TiO_2 white paint as the emitter, respectively. In the same period, Givoni [25] proposed another design of a passive RC system that can provide heating and cooling for buildings. The field started to attract more attention from researchers during the 1990s. During the decade, besides explorations that focused on the cooling power of emitter materials [26–30], some proposed RC systems involving working fluid to extract the cooling and other elements such as thermal storage [31–33] and desiccant [34] to improve the system's performance. Since then, the number of explorations of the application of RC in buildings has grown significantly.

There are different classifications of RC technologies applied in buildings. Erell and Santamouris [15] classified RC technologies into two categories based on how the RC system is utilized, namely movable insulation and heat exchangers. In an RC system with movable insulation, the emitter, which was actually a solar thermal collector, was protected from solar radiation at daytime and exposed to the sky at nighttime by turning the insulation off from the emitter [31,35]. In contrast, in an RC system with a heat exchanger, a working fluid, either water or air, was used as a medium to "carry the coldness" of the emitter to the building interior [16,36]. On the other hand, Zeyghami et al. [16] classified the RC technologies into two categories based on working time, namely nocturnal and diurnal. Nocturnal cooling consists of two general designs, i.e., a gray emitter which emits in the whole range of the wavelength, and a selective emitter which was designed to have emissivity higher or lower at a certain wavelength. Meanwhile, diurnal RC prefers to be equipped with selective emitter material and assisted with a cover shield.

The classifications of RC technology that have been performed by researchers mark a historical or rather a sequential development of RC technology. In this review, we classify RC technologies based on the type of improvement carried out by researchers in order to obtain technology applicable to buildings. The first category is "material improvement", which includes studies that focus on new materials or that enhance the current materials for emitters. The second category is "design improvement", i.e., researchers tried to modify the panel configuration, design, or supporting element to improve the emitter performance. The last category is "combination with other technologies", which includes applications of RC "to assist" or "with the assistance of" other technologies. Table 1 summarizes the classifications of improvement strategies and the reported performance.

Table 1. Improvement strategies for RC technology application in buildings.

Researcher	Category	Time	Improvement Strategy	Maximum Cooling Power/Minimum Temperature
[37]	Emitter material improvement	Nocturnal	Film-based emitter	energy saving for cooling up to 26–49%
[38]			Film-based emitter	43 W/m^2
[39]			Photonic emitter	5 °C below ambient
[40]			Photonic emitter	5.2 °C below ambient
[41]		Diurnal	Film-based emitter	120 W/m^2
[42]			Film-based emitter	not available (N/A)
[43]			Film-based emitter	2.5 °C below ambient
[8]			Film-based emitter	4.2 °C below ambient
[44]			Film-based emitter	95.1 W/m^2
[45]			Photonic emitter	110 W/m^2
[46]			Nanoparticle-based emitter	25.5 °C below ambient
[47]			Nanoparticle-based emitter	35 °C below ambient
[48]			Photonic emitter	N/A
[49]			Photonic emitter	14.3 W/m^2
[50]			Photonic emitter	7.7 ± 0.2 °C below ambient
[51]	Cover material improvement	Nocturnal	Film-based cover	23 W/m^2
[52]			Film-based cover	175 W/m^2
[53]			Film-based cover	N/A
[54]			Film-based cover	N/A
[55]		Diurnal	Photonic cover	50 W/m^2
[56]	Design improvement	Nocturnal	Design aspect: water contact with the emitter, insulation	97.8 W/m^2
[11]			Design aspect: construction material	2.5 °C below ambient
[57]			Design aspect: water contact with the emitter	52 W/m^2
[58]			Design aspect: air duct	90 W/m^2
[59]			Design aspect: insulation, air duct	2.5–4 °C below ambient
[60]			Design aspect: insulation	38 W/m^2
[61]			Design aspect: insulation	N/A
[62]			Design aspect: cover, air duct	1–6 °C below ambient
[63]		Diurnal	Design aspect: insulation	37 °C below ambient through a 24 h cycle
[64]			Design aspect: glazing and convection scheme	100 W/m^2
[65]			Design aspect: orientation	7.4 °C below ambient
[66]			Design aspect: appearance	3.9 °C below ambient

Table 1. *Cont.*

Researcher	Category	Time	Improvement Strategy	Maximum Cooling Power/Minimum Temperature
[67]	Combination	Nocturnal	Trombe wall	energy saving for cooling up to 53%
[30]			Wall material	55.8 W/m^2
[68]			Wall material and insulation, cold water storage	87 W/m^2
[69]			Solar Collector, phase change material (PCM)	N/A
[70]			Photovoltaics (PV)	128.5 W/m^2
[71]			Solar Collector	50.3 W/m^2
[72]			Cold storage	N/A
[73]			Solar Collector	27.3 W/m^2
[74]			PV, heating, ventilation, and air conditioning (HVAC) system	123.9 W/m^2
[75]			PV	41.7 W/m^2
[76]			HVAC	N/A
[77]			Solar Collector and PV, cold water storage	75 W/m^2
[78]			PCM	energy saving potential can reach 77% for low-rise buildings
[79]			Desiccant	5.5–7 °C below ambient
[34]			Solar Collector, desiccant	energy saving up to 7400 kWh per year
[80]			PV, solar collector, HVAC	N/A
[81]			HVAC	energy saving for cooling up to 46% for
[82]			Radiant cooling, air handling unit (AHU)	18.1 W/m^2
[83]			Fan or HVAC	5–10W/m^2
[84]			Ground coupled heat pump	energy saving 10.22% compared to conventional ground heat pump
[85]			PV, solar collector	72 W/m^2
[86]			HVAC	N/A
[87]			Thermosyphon and cold water storage	energy saving for cooling up to 8%
[88]			Solar Collector	36.61 W/m^2
[32]			Heat pipe	14.5 W/m^2
[17]			Photovoltaic thermal (PV/T)	65 W/m^2
[89]			Thermosyphon and cold water storage	N/A
[25]			Solar Collector	4–5 °C below ambient
[90]			Solar Collector	55.1 W/m^2
[91]			Solar Collector	40 W/m2
[33]			Thermosyphon and cold water storage	15 °C below ambient
[31]			Thermal mass	77.2 W/m^2

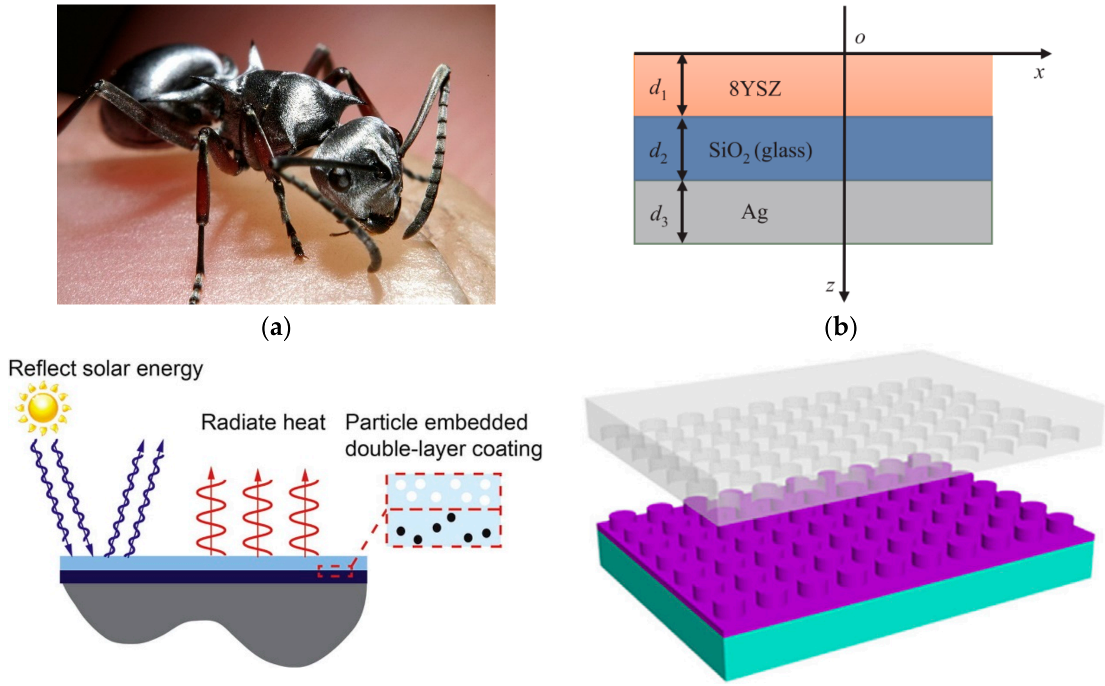
Table 1. *Cont.*

Researcher	Category	Time	Improvement Strategy	Maximum Cooling Power/Minimum Temperature
[92]			PV	72.94 W/m^2
[93]			Solar Collector, HVAC	4.7 °C below ambient
[94]			Water tank	8.4 °C temperature reduction
[95]		Diurnal	HVAC	16 W/m^2
[96]			HVAC	more than 200 W/m^2
[97]			Thermoelectric, cold water storage tank	daytime and nighttime cooling of the radiative sky cooling subsystem contribute to 55.0% and 45.0% of annual cold generation, respectively
[98]			Attic insulation	energy saving for cooling up to 3.7–11.8 kWh/m^2
[99]			Cold water storage, radiant cooling in the room	12.5 W/m^2
[100]			PCM, thermosyphon	energy saving for cooling up to 25%
[101]			PCM, wall material	energy saving for cooling up to 47.9%
[102]			PCM, cold water storage	energy saving for cooling up to 10%
[103]			Wall material and insulation	50 W/m^2 on the wall, and 120 W/m^2 on the roof
[104]			Shading device	reduces solar gain by up to 40%
[105]			Glazing	energy saving for cooling between 40.9–63.4%

3.1. Material Improvement

The development of nanomaterial technology has helped to increase the cooling power of RC materials. The material improvement involves two parts, namely emitter material and convection cover material. Detailed reviews of the emitter materials have been carried out by Zhao et al. [14] and Family and Menguc [106]. In the work of Zhao et al. [14], they categorize the material technologies for passive RC into four categories, i.e., a natural emitter, film-based emitter, nanoparticle-based emitter, and photonic emitter. Examples of these different emitters are shown in Figure 4. In this review, only some material examinations that are relevant to the application of RC in buildings are included.

There are at least three goals in the RC emitter material field of study, namely, improving cooling power in daytime [12], improving performance in humid conditions [44], and making a cost-efficient material [25,58]. Efforts on daytime RC were conducted using different approaches by material researchers, i.e., film-based emitters [8,41–44], nanoparticle-based emitters [46,47], and photonic emitters [45,48–50]. The engineered material must reflect most of the solar and atmospheric radiation and at the same time be able to produce thermal radiation in the specific atmospheric window band. The film-based emitter could produce all-day cooling between 2–9 °C for buildings on a typical sunny day in northern US latitudes [41]. The photonic emitter recorded a 110 W/m^2 cooling power under direct sunlight [45]. Further, nanoparticle-based emitters in the works of Liu et al. [46] and Kim and Lenert [47] were also recorded at sub-ambient temperature at daytime, with 25.5 °C and 35 °C below ambient, respectively.



(**a**) (**b**) (**c**) (**d**)

Figure 4. Different mechanism used in four categories of passive RC materials: (**a**) natural emitter, a mechanism found in Saharan silver ants [107] (reprinted from Solar Energy Materials and Solar Cells, 206, Jeong et al., Daytime passive radiative cooling by ultra-emissive bio-inspired polymeric surface, 110296, Copyright (2020), with permission from Elsevier); (**b**) film-based emitter design by Fan et al. [44] (reprinted from Applied Thermal Engineering, 165, Fan et al., Yttria-stabilized zirconia coating for passive daytime radiative cooling in humid environment, 114585, Copyright (2020), with permission from Elsevier); (**c**) nanoparticle-based emitter design by Huang and Ruan [108] (reprinted from International Journal of Heat and Mass Transfer, 104, Huang and Ruan, Nanoparticle embedded double-layer coating for daytime radiative cooling, 890–896, Copyright (2017), with permission from Elsevier); (**d**) photonic emitter design by Gao et al. [50] (reprinted Solar Energy Materials and Solar Cells, 200, Gao et al., Approach to fabricating high-performance cooler with near-ideal emissive spectrum for above-ambient air temperature radiative cooling, 110013, Copyright (2019), with permission from Elsevier).

In the subtropical climate, daytime RC emitters in the work of Jeong et al. [49] give a remarkable result, which is 7.2 °C below ambient at daytime. However, in the region of tropical climate with higher humidity, daytime RC is hardly achieved [39,40,44]. The best results in experimenting with RC materials for humid climate came from an enhanced specular reflector (ESR) material by 3M [109] that could be at sub-ambient temperature on a very humid and cloudy night [39,40].

Despite many scientists pursuing higher RC power both in the daytime and humid conditions, only a few have focused on the affordability of the materials. For instance, Givoni [25] and Erell and Etzion [58] proposed cheaper RC emitter options, but their examination resulted in a very low cooling power of RC compared to the other materials. Current high-performance RC materials are still expensive to produce and have limited durability [8].

In terms of convection cover materials, the spectral properties and durability are key issues. Benlattar et al. [53,54] are among the first to modify the spectral properties of convection cover. Using a chemical solution deposition method, they create a cadmium sulfide (CdS) thin film that is transparent for infrared radiation in the 8–13 μm band. They estimated a temperature reduction of 65 K between the uncovered nocturnal emitter and the covered one [54]. In another study, Naghshine and Saboonchi [52] compared different thin film multilayer structures for RC convection cover. Among the 30 possible multilayers structures from a combination of 16 thin film materials, structures that involved cubic ZnS in their layers are better at protecting the RC emitter from parasitic heat loss during the day and night. Their schematic thin film multilayer structure is shown in Figure 5. Moreover, investigations for durable alternatives of convection cover were conducted by Bathgate and Bosi [51]. They found that zinc sulfide (ZnS) was the most promising material for the RC emitter cover, as shown in Figure 6.

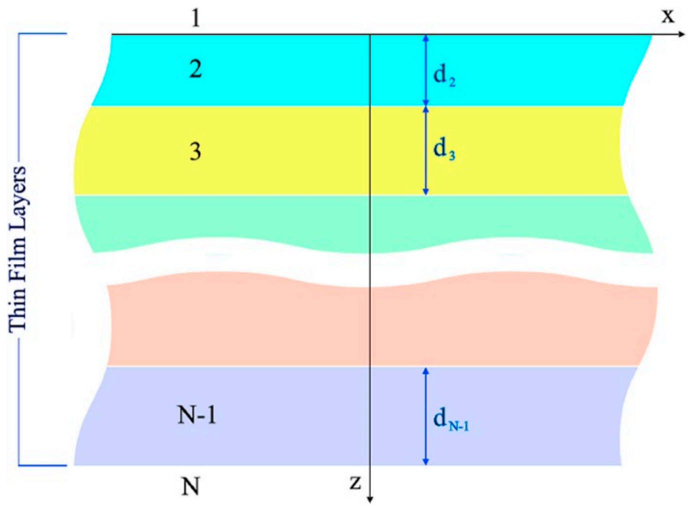


Figure 5. Multilayer structure thin film scheme of Naghshine and Saboonchi [52] (reprinted from Optics Communications, 410, Naghshine and Saboonchi, Optimized thin film coatings for passive radiative cooling applications, 416–423, Copyright (2018), with permission from Elsevier). They investigated 30 combinations of layers.

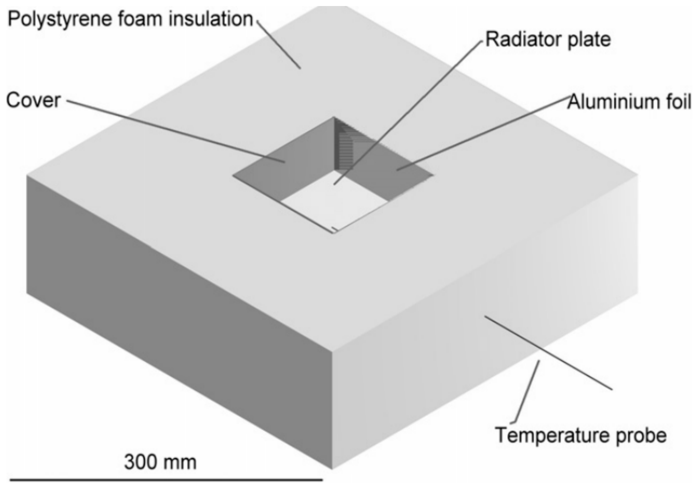


Figure 6. Typical RC panel design with insulation and convection cover [51] (reprinted from Solar Energy Materials and Solar Cells, 95/10, Bathgate and Bosi, A robust convection cover material for selective radiative cooling applications, 2778–2785, Copyright (2011), with permission from Elsevier).

3.2. Design Improvement

Besides enhancements in RC materials, improvements in the design of RC systems have also been proposed. Most researchers focused on two main aspects of RC system design, namely emitter insulation, and emitter contact to the working fluid. The emitter's insulation is one of the crucial elements in the roof-integrated RC systems designed by Dimoudi and Androutsopoulos [56] and Khedari et al. [62]. Craig et al. [110] went further by suggesting that improving the RC emitter's insulation on the roof not only increases its performance, but by modifying the configuration of the roof's insulation, a conventional roof material could even be an RC emitter. Figure 7 shows the roof-integrated RC system and how the roof insulation was structured [56].

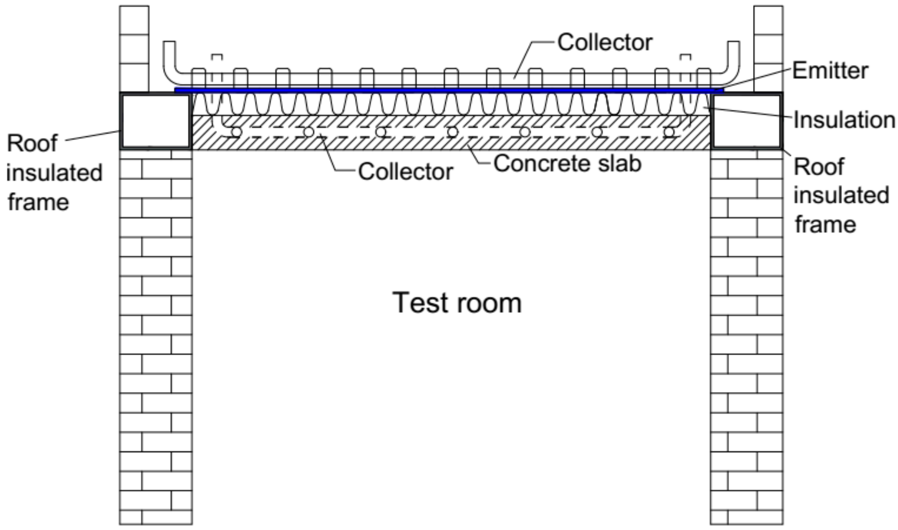


Figure 7. Proposed configurations of insulation for roof—integrated solar collector—RC emitters by Dimoudi and Androutsopoulos [56] (Adapted from Solar Energy, 80/8, Dimoudi and Androutsopoulos, The cooling performance of a radiator based roof component, 1039–1047, Copyright (2006), with permission from Elsevier).

Regarding the insulation from convection between the emitter material and the cover shield, some researchers proposed the use of vacuum to minimize parasitic thermal load to the emitter [60,63]. Chen et al. [63] are the first to experiment with a vacuum-enhanced RC emitter. Their design intends to achieve daytime RC and succeeds in obtaining a maximum of 42 °C below ambient under intense solar radiation. Tso et al. [60], however, did not achieve a daytime RC effect but could deliver nocturnal RC in a more humid climate in Hong Kong. Their design, shown in Figure 8, could provide a cooling power of 38 W/m^2 at night.

A different approach was used in the cover design by Falt et al. [61,64]. They proposed a triple-glazing skylight which features high absorptivity. The gas blocks the infrared part of solar radiation, and, thus, reduces heat gain to the building's interior and at night releases heat via radiation to the sky. The novelty of their design lies in the middle that could tilt, allowing the formation of a gap between the glass and the skylight's edge. This gap, in turn, enables the gas to move between the upper and lower part of the skylight, thus, when the upper gas is cooled by nocturnal radiation, it is replaced by the warmer lower gas. See Figure 9 for the illustration of the design.

Moreover, to utilize cooling from an RC emitter in the building, the most feasible way is by using a working fluid, which can either be a water-based or an air-based system. Furthermore, the water-based system is divided into an open system and a closed system. In the water-based open system, the cold storage water directly contacts the RC emitter, without any circulation of any working fluid. In the closed system, however, circulated water is used as a working fluid to deliver coldness either to storage or to a heat exchanger. The conceptual drawing of the typical water-based and air-based RC system is shown in Figure 10. The advantages and disadvantages of the water and air-based system are already summarized by Lu et al. [7] and Zhang et al. [81]. The lower installation cost and the simplicity of the system are among the advantages of the air-based system, while the water-based system is better in terms of cooling performance because water has a higher heat capacity than air. It is important to note that the effectiveness of the heat transfer between the emitter and the fluid has also been the focus of investigations for both the water- and air-based RC [11,57–59]. The investigations prescribed the optimum mass flow rate of the fluid to obtain the maximum cooling effect, as Hosseinzadeh and

Taherian [57] indicated that the mass flow rate of the fluid is critical in achieving the best cooling performance of an RC emitter.

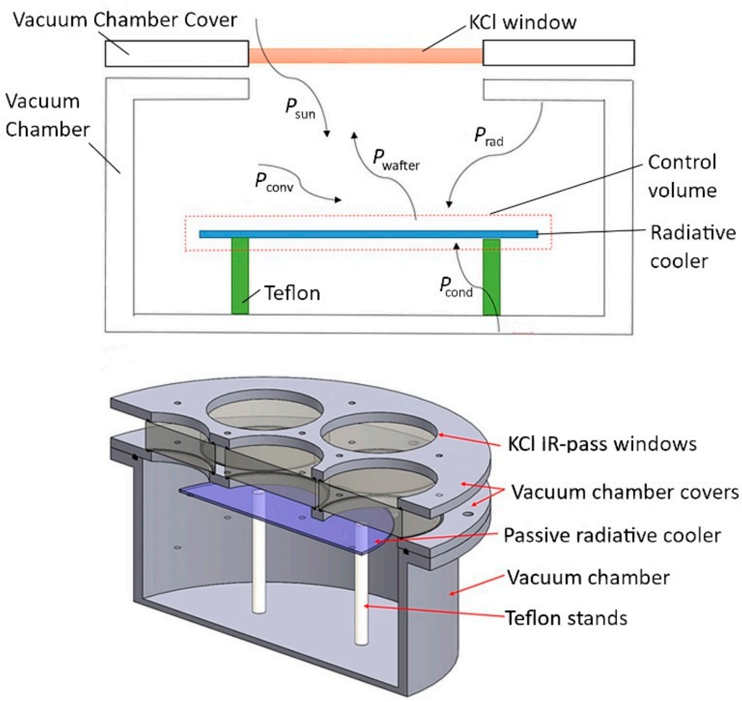


Figure 8. Design of vacuum chamber as insulation and part of the convective cover for the RC emitter [60] (reprinted from Renewable Energy, 106, Tso et al., A field investigation of passive radiative cooling under Hong Kong's climate, 52–61, Copyright (2017), with permission from Elsevier).

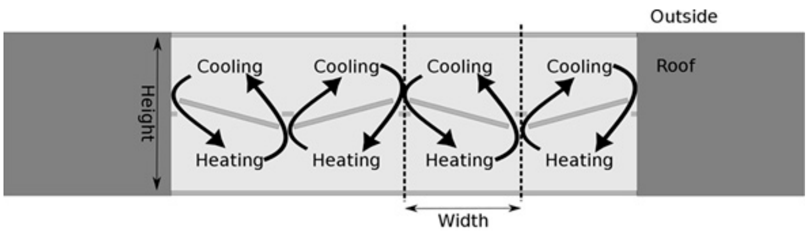


Figure 9. Design of a triple-glazing skylight that can operate as an RC emitter by incorporating a high-absorptivity gas. RC occurs for the upper gas, while the lower gas obtains heat from the building's interior. The middle glass then switches the cool and warm air in the upper and lower part of the glazing, enabling the cycle to continue [61] (reprinted from Building and Environment, 126, Falt et al., Modified predator-prey algorithm approach to designing a cooling or insulating skylight, 331–338, Copyright (2017), with permission from Elsevier).

Other small design considerations were also studied, such as the aesthetic appearance of the emitter. The appearance of the RC emitter is obviously interesting for architects and might accelerate the implementation of RC in building design. Lee et al. [66] and Son et al. [111] employed different techniques to create colored emitters. By adding a photonic nanolayer in the order of metal–insulator–metal (MIM) below the emitter, Lee et al. [66] could decorate their RC emitter. The MIM layers consisted of Ag-SiO_2-Ag, and a variation of the colors was achieved by varying the thickness of the SiO_2 layer. On the other hand, Son et al. [111] coated the emitter with silica-embedded perovskite to color it. Figure 11 displays the colored RC emitter by Son et al. [111]. Both colored RC emitters could achieve sub-ambient temperature during the daytime.

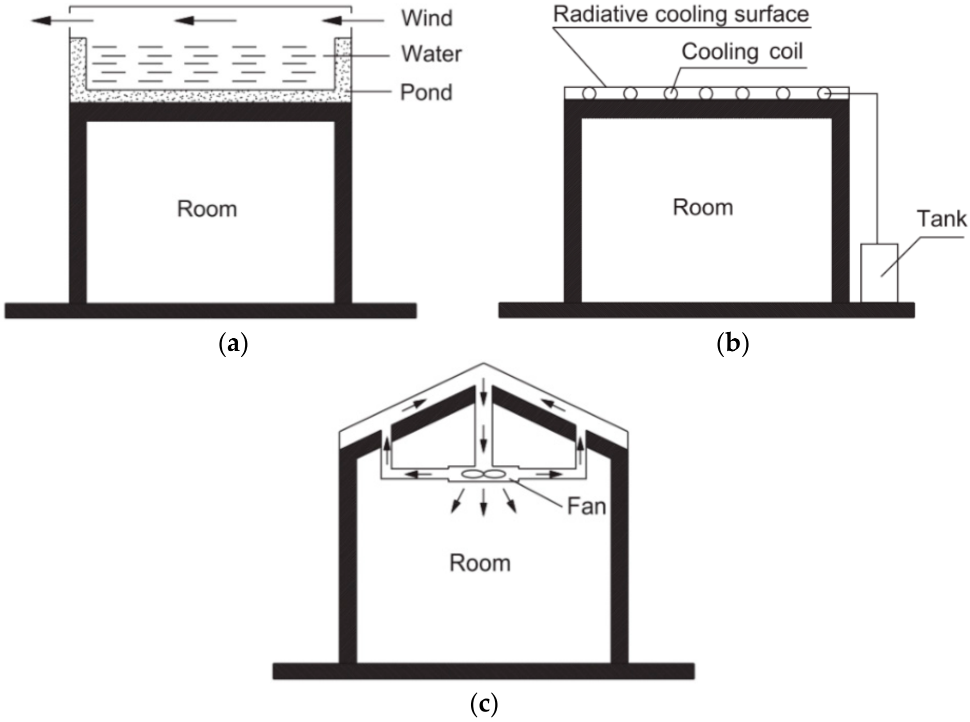


Figure 10. Configuration of different ways to utilize cooling from the RC emitter: (**a**) water-based open system; (**b**) water-based closed system (**c**) air-based system [81] (reprinted from Applied Energy, 224, Zhang et al., Energy saving and economic analysis of a new hybrid radiative cooling system for single-family houses in the USA, 271–281, Copyright (2018), with permission from Elsevier).

Figure 11. Samples of colored daytime RC emitter researched by Son et al. [111] (reprinted from Nano Energy, Son et al., Colored emitters with silica-embedded perovskite nanocrystals for efficient daytime radiative cooling, 105461, Copyright (2020), with permission from Elsevier).

3.3. Combination with Other Technologies

Application of RC in buildings often appears in combinations with other cooling technologies. These combinations can be categorized as active systems and passive systems. Many of the water-based RC systems are active systems, i.e., assisted by a pump to circulate the water. The passive water-based system is found where a thermosyphon mechanism drives the flow of the fluid. Air-based systems, on the other hand, are more often found as a passive system. Some strategies involve a fan as the active part of an air-based RC to maintain the airflow to the RC panel. A detailed comparison for the precedent of RC combinations is shown in Table 2.

Table 2. Comparison of different means of architectural implementation of RC.

Researcher	Architectural Feature	Means of Implementation		Combination
[25]	Roof	Passive system	Air-based	Solar Collector
[31]			Air-based	Thermal mass
[30]			Air-based	Thermal mass
[98]			Air-based	Attic Insulation
[94]			Water-based open system	Water tank
[93]		Active system	Air-based	Solar Collector, HVAC
[83]			Air-based	Fan or HVAC
[79]			Air-based	Desiccant
[34]			Air-based	Solar Collector, Desiccant
[80]			Air-based	PV, Solar Collector, HVAC
[74]			Air-based	PV, HVAC
[75]			N/A	PV
[76]			Water-based closed system	HVAC
[77]			Water-based closed system	Solar Collector and PV, cold water storage
[78]			Water-based closed system	PCM
[81]			Water-based closed system	HVAC
[82]			Water-based closed system	Radiant cooling, HVAC
[84]			Water-based closed system	Ground coupled heat pump
[85]			Water-based closed system	PV, Solar Collector
[86]			Water-based closed system	HVAC
[87]			Water-based closed system	Thermosyphon and cold water storage
[32]			Water-based closed system	Heat pipe
[17]			Water-based closed system	PV, Solar Collector
[89]			Water-based closed system	Thermosyphon and cold water storage
[90]			Water-based closed system	Solar Collector
[33]			Water-based closed system	Thermosyphon and cold water storage
[95]			Water-based closed system	HVAC
[96]			Water-based closed system	HVAC
[99]			Water-based closed system	Cold water storage
[102]			Water-based closed system	PCM, Cold Water Storage
[88]		N/A	Air-based	Solar Collector
[92]			N/A	PV
[103]	Roof and Wall	Passive system	Air-based	Wall material and insulation
[112]		Passive or active	Air or water-based	Temperature-regulating module
[113]	Wall	Passive system	Air-based	Trombe wall
[67]		Passive system	Air-based	Trombe wall
[100]		Passive system	Water-based closed system	PCM wall
[101]		Passive system	Water-based closed system	PCM wall
[68]		Active system	Water-based closed system	Wall material and insulation, cold water storage
[105]	Window or skylight	Passive system	Air-based	Glazing material
[114]		Passive system	Air-based	Glazing material

3.3.1. Active System

Specifically, the solar collector [25,34,77,90], photovoltaics (PV) [17,76,77,85], air conditioning (AC) [81,83,86,95,96], and cold water storage [33,89,99,102] are among the frequently studied combinations for the active systems. Givoni [25] is among the first to utilize a solar collector panel as an RC panel. The strategy is to utilize the absorber of the solar collector during the day as an emitter at night. This so-called dual-functional collector is further developed using more advanced techniques and materials [17,88,90]. Spectral-selective coating on the solar thermal absorber was used, as well as a low-density polyethylene (LDPE) film as the cover, replacing the glass cover in the conventional solar thermal collector. The latest results by Hu et al. [90] produce 55.1 W/m^2 cooling power at night. Their design is illustrated in Figure 12.

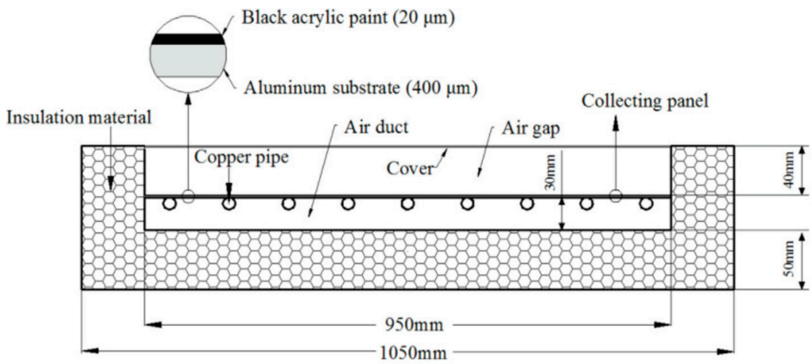


Figure 12. Cross-section schematic drawing of photo-thermal and RC (PTRC) design by Hu et al. [90] (reprinted from Renewable Energy, 139, Hu et al., Experimental study on a hybrid photo-thermal and radiative cooling collector using black acrylic paint as the panel coating, 1217–1226, Copyright (2019), with permission from Elsevier).

Combining PV with RC was initially visualized in the design of Harbeman House by Saitoh and Fujino [77], a so-called sustainable house proposal that attempted to integrate various sustainable technologies in the house. A more persistent study on the possible application of the PV-RC combination is conducted by Zhao et al. [70,75,92,115]. Using photonic material, they develop several strategies in PV-RC ranging from nocturnal to diurnal cooling. In terms of building energy consumption, PV-RC can be more beneficial because the combined electricity and cooling energy resulting from the system is more than the output energy from PV alone [74,75]. Both RC combinations with solar thermal and PV can be divided into two types when installed on the roof, i.e., similar orientation or opposite orientation. With similar orientation, the researchers placed the RC panel on the same side of the roof as the solar collector or PV, normally the sun-facing side [17,70,88,90]. In contrast, the opposite orientation used the opposite side of the roof to reduce solar heat gain to the emitter [75,77,85].

Furthermore, RC is also commonly used to assist HVAC systems. Usually, the emitter is used to provide chilled water for the cooling coil of AC, enabling the system to be more energy efficient [95,96]. The design by Jeong et al. [95], for instance, used two types of cooling coils, conventional cooling coils and RC-supplied cooling coils, thus, RC acted as a supplementary cooling supplier. The system was claimed to be able to reduce cooling energy consumption by 35%. Another variant of the RC-HVAC system came from Zhang et al. [81], who added a cold water storage to stock cooling energy from RC. Figure 13 displays the schematic diagram of an RC-assisted HVAC system.

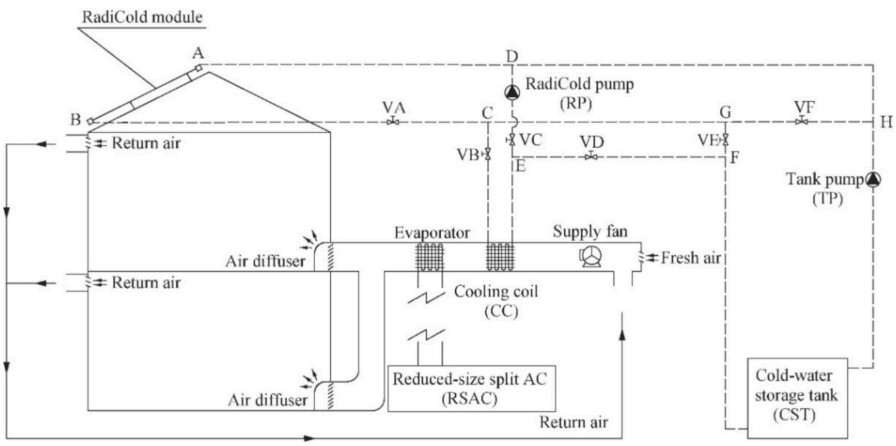


Figure 13. Schematic of a typical RC-assisted HVAC system [81] (reprinted from Applied Energy, 224, Zhang et al., Energy saving and economic analysis of a new hybrid radiative cooling system for single-family houses in the USA, 271–281, Copyright (2018), with permission from Elsevier).

3.3.2. Passive System

In terms of the passive system, RC has been combined with more diverse techniques such as wall-mounted RC [68,98,103], phase change material (PCM) [100,101], thermal mass [30,31], and the Trombe wall [67,113]. Oliveti et al. [103] attempted to include thermal radiation from the wall to the sky to the overall heat exchange model of a wall. Yong et al. [68] went further than developing a mathematical model by proposing an RC system mounted on the wall. Their system is a dual-functional solar collector that can provide heating in winter and cooling in summer, as shown in Figure 14. However, the system is an active system, involving pumps to circulate water to be stored in the cold and hot water storage. The fully passive implementations of a wall-mounted RC were performed by Shen et al. [100] and He et al. [101]. Their designs are quite similar in principle, using the thermosyphon method to extract cooling from the wall and storing the heat in a PCM (see Figure 15). In terms of cooling performance, the wall-mounted dual-functional heating–cooling emitter was predicted to be able to reduce building energy consumption by 47.9% [68].

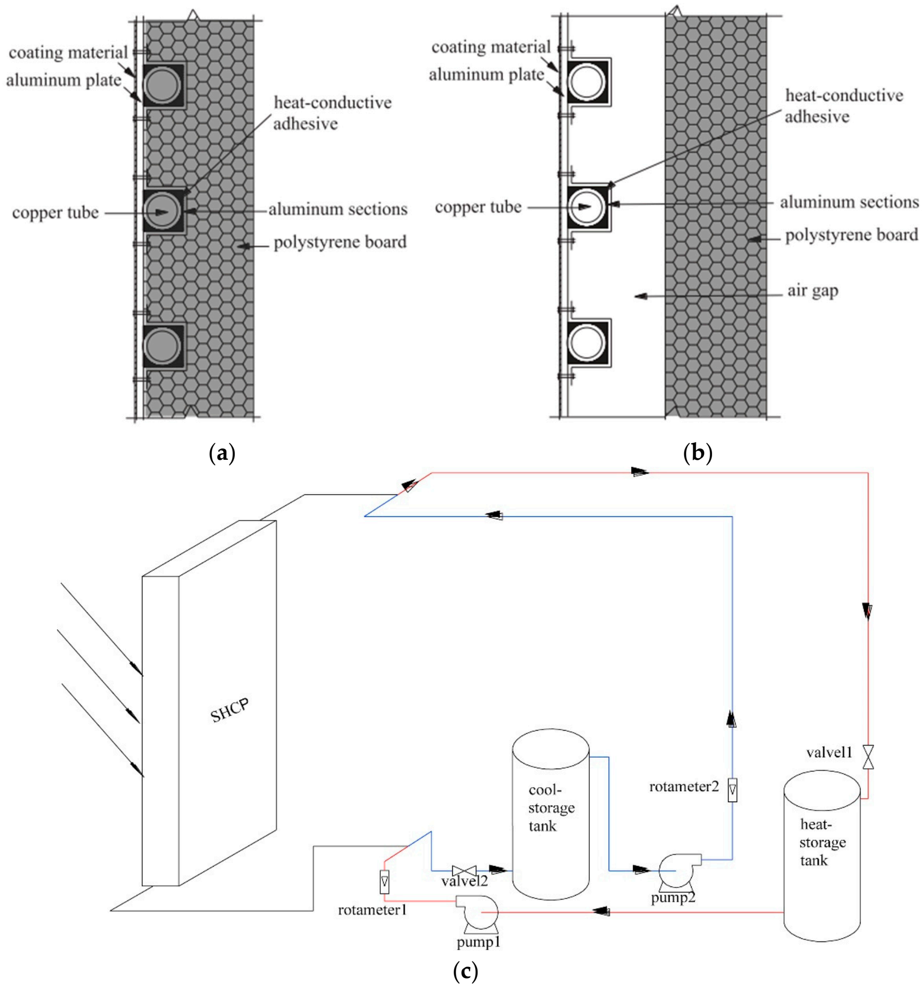


Figure 14. Structure of solar absorber that serves, i.e., two functions for heating and cooling as designed by Yong et al. [68]: (**a**) design without an air gap for insulation purposes; (**b**) design with an air gap for an area with nighttime ambient temperature that is low enough to be used as cooling, nocturnal cooling thus provided by both the sky and the surroundings; (**c**) schematic diagram showing the mechanism in which the dual-functional system works—red line for heating, blue line for cooling (reprinted from Renewable Energy, 74, Yong et al., Performance analysis on a building-integrated solar heating and cooling panel, 627–632, Copyright (2015), with permission from Elsevier).

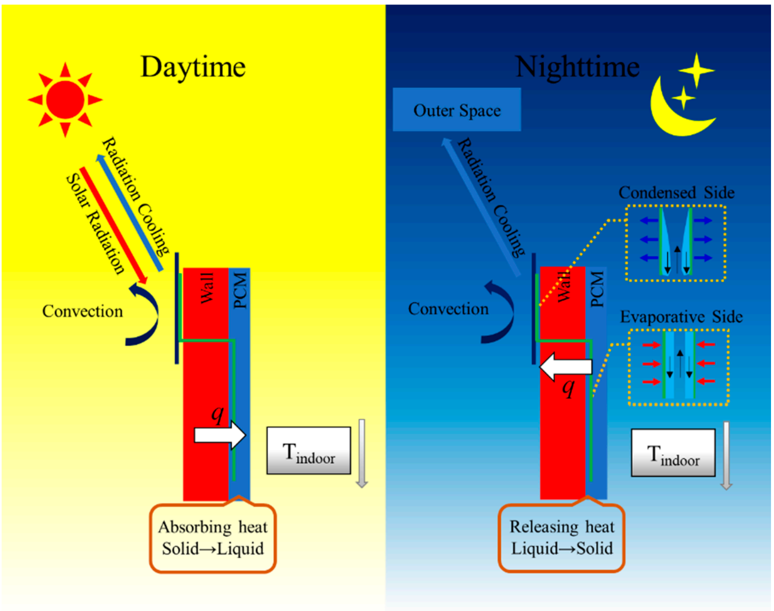


Figure 15. Dual-functional RC-PCM wall design by He et al. [101]. During the daytime, the absorbed heat is stored by PCM and is later released at night via RC, thus, the temperature of the room can be kept comfortable, and the PCM can "recharge" (reproduced from Energy and Buildings, 199, He et al., Experimental study on the performance of a novel RC-PCM-wall, 297–310, Copyright (2019), with permission from Elsevier).

Whereas the aforementioned researchers used PCM to regulate the heat gain and loss in the wall or building enclosure, some researchers have attempted to use insulation and thermal mass to regulate heat transfer from an RC emitter to the building. Etzion and Erell [31] mentioned at least two functions of thermal mass or other types of thermal storage strategies when combined with nocturnal RC for a building. Firstly, thermal mass can absorb the excessive heat received by the RC emitter during the daytime. Secondly, it maintains the cooling rate of the RC emitter to a desired rate, thus, heat does not dissipate rapidly from the building, and the RC emitter becomes steady. Thus, Etzion and Erell [31] examined the best location for placing thermal mass. They found that thermal mass should be placed on the roof or, in more general terms, should be closely coupled with the radiative emitter [31].

Furthermore, Liu et al. [112] also developed a temperature-regulating module (TRM) for solar heating and RC. The TRM consists of polyethylene film as the convection cover, a porous RC material, an aluminum sheet, and a solar absorber (Figure 16). The layer order was reversed for heating mode. The TRM maintained a maximum indoor temperature of 27.5 °C in the hottest days of summer and 25 °C for some hours on winter days. The heating and cooling provided by the TRM correspond to 42.4% saving in the electricity bill.

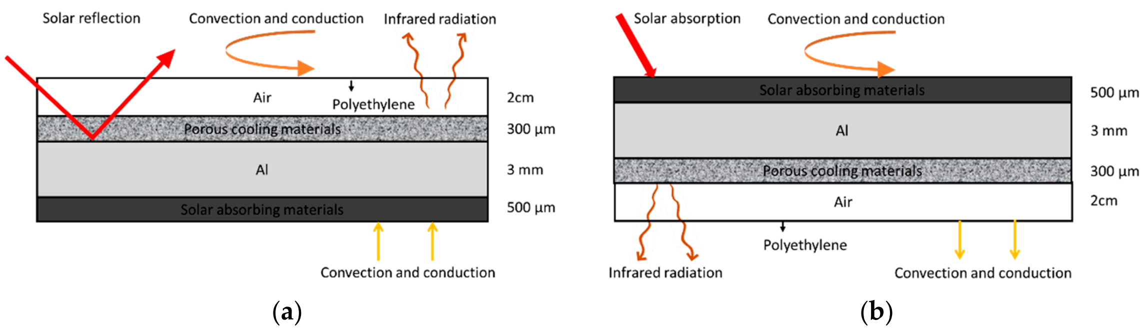
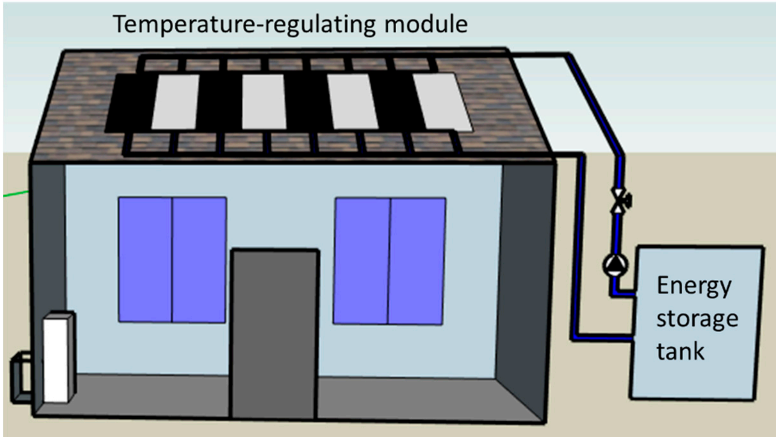


Figure 16. *Cont.*



(c)

Figure 16. Temperature-regulating module by Liu et al. [112]: (**a**) cooling mode; (**b**) heating mode; (**c**) when applied on the roof (reproduced from Energy Conversion and Management, 205, Liu et al., Research on the performance of radiative cooling and solar heating coupling module to direct control indoor temperature, 112395, Copyright (2020), with permission from Elsevier).

4. Architectural Features of Current Radiative Cooling Systems

As the previous section summarizes, RC for buildings has been prototyped in very diverse ways. Design alternatives are even numerous when RC is combined with other cooling technologies. Nevertheless, analysis of the RC systems from an architectural point of view should be conducted before it is widely accepted by the architectural community as one of the promising passive design strategies for sustainable buildings [19]. One way of doing so is by analyzing the precedents of architectural features involved in the proposals of passive applications of RC. As compiled in Table 2, some building components or architectural features that have been involved in passive RC systems are revealed. Theoretically, the roof is the best location to place an RC emitter compared to other building envelopes. However, architects might want more flexibility in their design, and few researchers have applied RC in the wall and façade. These researches, although very few in number, offer alternatives in architectural implementation.

4.1. Roof

Installing the RC emitter on the roof is the simplest and most promising way. Besides its highest sky view factor compared to the wall or other building components, the roof is also a common place for building service installations. Available roof-integrated passive RC systems consist of both air- and water-based systems. The roof water-based RC is an open system which is quite similar to a roof pond design [94,116] (Figure 17). Disadvantages of the roof water-based RC are more or less the same as the roof pond, such as difficulty in waterproofing the roof, additional load to the roof structure, and maintenance of the cleanliness of the water. It can also only be installed on top of flat roofs and affects the accessibility of the roof for other uses [117].

Moreover, the roof air-based system offers more techniques. The most straightforward use of an RC emitter was firstly proposed by Etzion [31], where the RC emitter is attached to a concrete roof slab. By this design, the cooling effect of the RC emitter is absorbed by the thermal mass of the roof slab and in turn transmitted to the room. Another air-based roof system uses an air channel to extract the cooling from the RC emitter [25,98]. By using an air channel attached to an RC emitter, cooling is provided by means of cool airflow from the air channel instead of convection of the interior air with the building envelops. This is arguably better for the distribution of the cool and fresh air. Figure 18 shows one example of how the air channel was used to extract cooling from the RC emitter [98]. In the design, the air was used for heat removal in the attic, although it can be further explored for the room's heat removal as well.

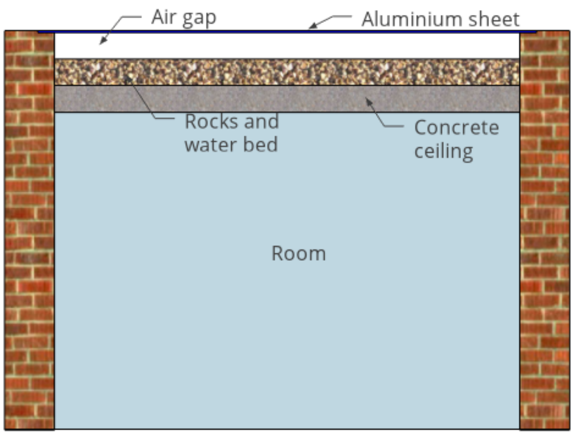


Figure 17. Water-based open system RC on the roof of a building [116] (reproduced from Renewable Energy, 29/11, Cheikh and Bouchair, Passive cooling by evapo-reflective roof for hot dry climates, 1877–1886, Copyright (2004), with permission from Elsevier).

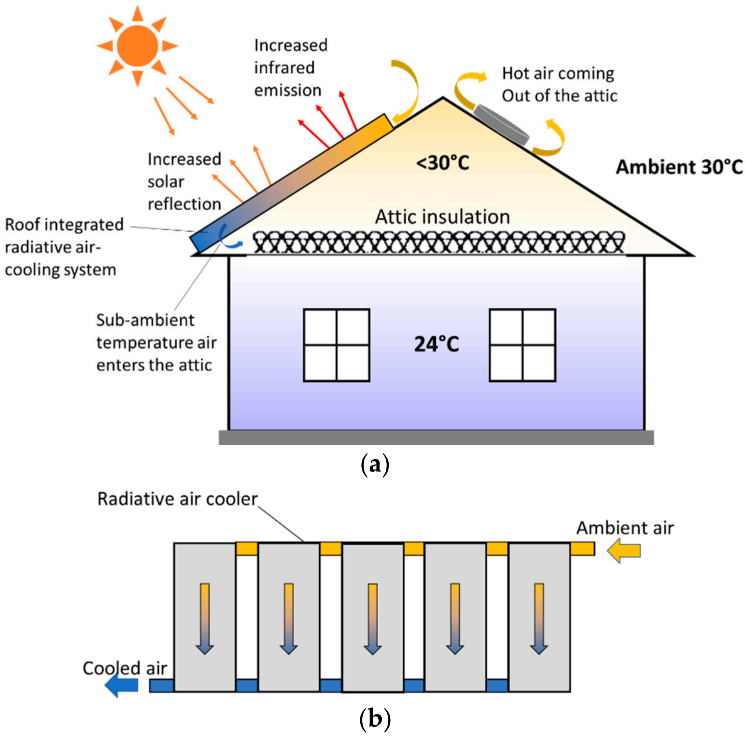


Figure 18. Air-based RC system on the roof using an air channel to utilize the cooling [98]: (**a**) illustration of how the system works to remove heat from the attic; (**b**) schematic of the air channel and the RC panel (reproduced from Energy and Buildings, 203, D. Zhao et al., Roof-integrated radiative air-cooling system to achieve cooler attic for building energy saving, 109453, Copyright (2019), with permission from Elsevier).

4.2. Wall

The second most appropriate architectural feature to place the RC emitter on is the wall. The wall has the advantage of providing a large surface when compared to the roof or other building envelopes. As with the roof RC, the wall RC also appeared in two systems, air-based and water-based systems. It is worth noting that most of the existing proposals on passive RC systems mounted on the wall are dual-functional (heating–cooling) modules. For instance, the air-based wall RC system is a combination with Trombe wall, which was developed by Sameti and Kasaeian [67] and consists of a glass cover and a thermal mass located directly behind the glass. The thermal mass function is to collect the sunlight entering the façade during heating mode and dissipate the heat to the night sky during cooling time. The glass cover is open during the heating days to protect it from solar radiation and closed during the heating nights to prevent radiative heat loss. The reverse is applied for cooling days. Nevertheless, it is important to note that an RC-Trombe wall system has some features that can affect its performance such as external glazing material, vents geometry and position, thermal storage, and Trombe wall area [118,119].

For the water-based RC wall, the system is accompanied by PCM to store the coldness and uses thermosyphon phenomena to extract it from the emitter, as described in Section 3 (see Figure 15) [101]. A similar design to that of He et al. [101] was also tested by Shen et al. [100]. Compared to the testing room with a brick wall, the cooling load in the RC-PCM wall room was 42% and 25% lower at ideal and moderate conditions. Furthermore, there are concerning factors that affect the performance of an RC-PCM wall system, i.e., the parasitic heat loss due to outdoor wind. Their system was not equipped with a convection cover, thus, the effect of wind speed was significant. The implementation of the RC-PCM wall in the testing room can be seen in Figure 19.

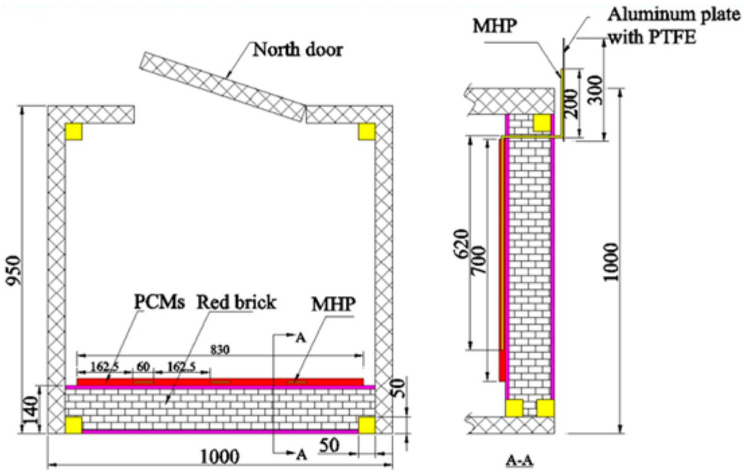


Figure 19. The drawing of an experimental room for an RC-PCM wall by Shen et al. [100]. The RC-PCM wall was mounted on the south wall. The measurement data from this room were compared with a conventional brick wall room (reprinted from Applied Thermal Engineering, 176, Shen et al., Investigation on the thermal performance of the novel phase change materials wall with radiative cooling, 115479, Copyright (2020), with permission from Elsevier).

4.3. Other Building Components

4.3.1. Glazing Material

Openings on the building envelope are the source of solar fenestration into the building's interior. Various glazing materials have been developed to reduce their transmissivity in the solar and infrared bands. Furthermore, researchers intended to also maximize thermal radiation of the glazing material in the atmospheric window band. With this strategy, the glazing materials not only reduce heat gain but also produce cooling for the building. Two prototypes, namely transparent film and coating to be added on top of glazing materials, have recently been developed [105,114,120]. Currently, the transparent RC materials are only studied for skylight application, as shown in Figure 20. Future development for transparent RC film or coating might be evaluated for window application.

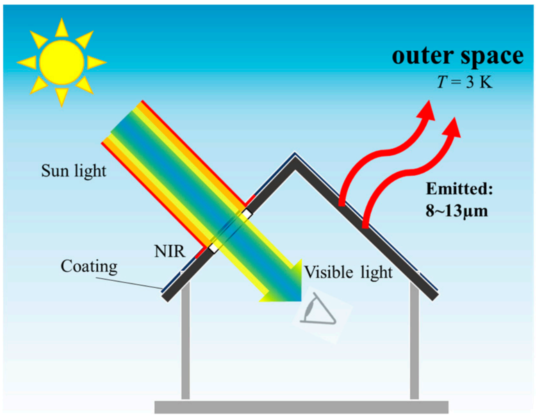


Figure 20. A transparent RC emitter used on a skylight to provide daylighting as well as passive cooling for buildings [114] (reproduced from Solar Energy Materials and Solar Cells, 213, Ziming et al., Low-cost radiative cooling blade coating with ultrahigh visible light transmittance and emission within an "atmospheric window", 110563, Copyright (2020), with permission from Elsevier).

4.3.2. Paints

Recently, paint was proposed as a means to act as a scalable RC emitter. It is well known by researchers of passive RC that the currently available technologies are not yet scalable and feasible for building use. Considering paint as a mature technology and always certainly used in buildings (either for roof, walls, or other parts of a building), for Mandal et al. [121], an RC paint might be the answer to the problem of scalability of RC technologies. For them, the material technologies have the capability to develop a scalable and effective RC paint. The current development of cool roof coating is an example of the success of material technologies to enhance paint performance. However, they also highlighted some general challenges for the development of RC paint besides the technical difficulties. The challenges are the assessment of geographical conditions in which RC paint benefits the most, as well as the examination of the effect of pollution, dirt, and dust on the durability and performance of the paint.

Furthermore, RC paint can also be seen in the perspective of the aesthetic appearance of RC surfaces. Currently, research on this aspect is scarce. The study conducted by Lee et al. [66] is one example of the attempt to answer the aesthetic appearance of an RC emitter (see Figure 21). Research on RC paint might promote the progress on aesthetic studies of RC surfaces.

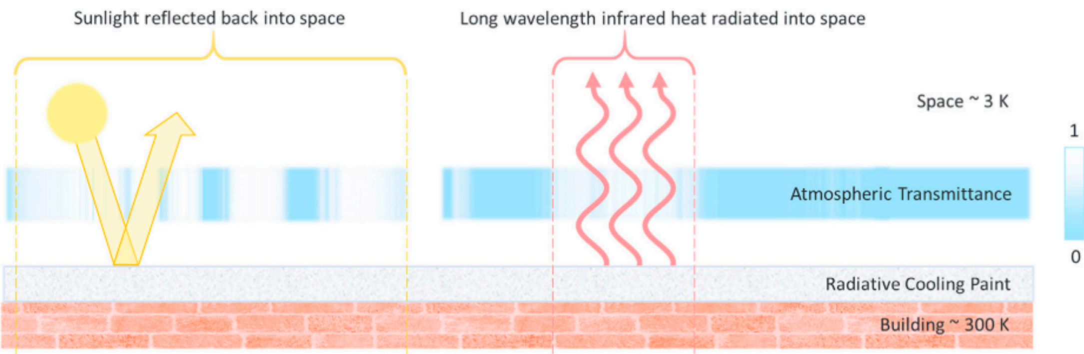


Figure 21. Schematic diagram showing the potential role of RC paints for buildings [121] (reprinted from Joule, 4/7, Mandal et al., Paints as a scalable and Effective Radiative Cooling Technology for Buildings, 1350–1356, Copyright (2020), with permission from Elsevier).

5. Outlook for Architectural Application of Passive Radiative Cooling

The previous sections have discussed the development of RC technologies and how they have been applied to reduce the cooling energy of buildings. From an architectural perspective, some issues regarding the implementation of passive RC in buildings arise from the discussions.

- In the range of the current RC power and the challenge to overcome the mismatch in cooling supply and demand, studies on the application of RC in buildings can search for an efficient RC system or effective storage mechanism. Additionally, exploration of the combination of RC with other passive or active cooling techniques should be continued and even extended, because in this way, the disadvantages of RC technologies can be compensated by the advantages of other cooling techniques. Moreover, in terms of exploration of potential RC combinations, there might be other passive design strategies in architecture, outside the cooling techniques, that have not yet been taken into consideration by RC researchers, such as natural ventilation and daylighting strategies. Therefore, a review on the type of strategies of passive design architecture that are suitable for combination with RC is still outstanding.
- Regarding architectural aspects, there are many considerations neglected by current RC studies. The roof may have an advantage in regard to the sky view factor, but another building element, such as the wall, may offer advantages in surface area as well as design flexibility. Additional façade elements on the wall, such as a shading device, secondary skin, cladding, and window, are potential locations for the RC emitter. In addition, the aesthetic aspect is also important. Thus, research on transparent and colored RC materials or even RC paints would encourage more flexibility in the architectural application.
- Following the notions on architectural aspects, another important point arises, that is, the lack of research on the integration of RC systems in building design. Observations of the implementation of the RC system into real buildings should be introduced. The design process of such an observation and the observation itself might reveal some influential details that have not yet been considered.
- Most of, if not all, the investigations of RC in buildings have focused on reducing cooling energy. Besides, the benefit of the RC system, if working ideally, may lead to healthy and comfortable buildings. This area of study, namely the contribution of passive RC in creating thermal comfort for building occupants as well as its further effect on health (and productivity in the working space), will eventually arise.
- Lastly, two general factors should not be forgotten, namely, the durability of the radiative material and the cost of the material. Since there are many studies still in the lab scale, these factors have not been calculated by many researchers. Nevertheless, these two aspects can be determinant in terms of real application. Architects and building owners usually prefer to directly know the cost of installation, saving potential, and payback period of the implemented RC systems. Full life-cycle analysis of the system can also be an object of study by researchers in the field.

6. Conclusions

The RC research field was revived by the development of new materials. There have been many high-performance RC materials that resulted from the experimentations. The present challenge in this field is to provide scalable and durable RC materials. Besides these two purposes, research on colored and transparent RC materials could also widen the application of RC in buildings. Likewise, pursuing RC paints might be an alternative way to create scalable and colorful emitters, and thus could attract more attention from the architectural community. Furthermore, the available RC materials have been implemented in various RC module designs, as their utilization to reduce cooling energy demand for buildings has also been conducted. Such efforts can continue to be pursued with emphasis on the combination of RC with other passive design strategies. The combination is not limited only to other passive cooling techniques but could also be carried out with natural ventilation, heat storage, daylighting, etc. In addition to this, the designs of building-integrated RC should begin to look at building components other than the roof to be the place for installation. Only a handful of building features have been involved in the current explorations such as walls and skylights.

Another research direction for the application of RC in buildings is the evaluation of the RC performance in terms of the occupant's health and comfort. The two indicators could be supplementary to the current performance evaluation, i.e., cooling power or energy saving. This is especially relevant when the RC is combined with other passive design strategies, which may require multi-perspective performance evaluation. At the latter stage, a life-cycle analysis of a building-integrated RC system could also be included. Nevertheless, the efforts to apply RC in buildings need to be more integrated into the architectural design. One way of achieving this is by implementation of the currently available RC materials or panels to a real building, which can be an existing building or a newly constructed building. This type of case study using real building would necessitate a design integration and could uncover some unanticipated aspects of building-integrated RC. Moreover, the uncovered aspects will be further examined in future studies in the field.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

RC	radiative cooling
PCM	phase change material
PV	photovoltaics
PV/T	photovoltaics thermal
AC	air conditioning
HVAC	heating, ventilation, and air conditioning
TRM	temperature-regulating module
LDPE	low-density polyethylene
MIM	metal-insulator-metal
ESR	enhanced specular reflector
$E_{B\lambda}$	spectral emissive power ($W{\cdot}m^{-2}{\cdot}\mu m^{-1}$)
T	temperature (K)
T_{amb}	ambient temperature (K)
$T_{emitter}$	emitter temperature(K)
A	emitter's area (m^2)
λ	wavelength λ (μm)
λ_{max}	the wavelength in which a blackbody emits maximum radiation (μm)
h	Planck's constant (6.626×10^{-34} J·s)
c_0	speed of light in vacuum (2.998×10^8 m· s^{-1})
n	refractive index (1 for vacuum)
k	Boltzmann's constant (1.3807×10^{-23} J·K^{-1})
Q_{net}	cooling power of the RC emitter (W)
Q_{sun}	radiation from the sun (W)
Q_{atm}	atmospheric radiation (W)
$Q_{cond+conv}$	parasitic heat loss from the RC emitter due to conduction and convection (W)
h_c	heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
ϵ	emissivity of the emitter
ϵ_{atm}	emissivity of the sky

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