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Effect of the spectrally selective features of the cover and emitter combination on radiative cooling performance

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ABSTRACT

Radiative cooling (RC) shows good potential for building energy saving by throwing waste heat to the cosmos in a passive and sustainable manner. However, most available radiative coolers suffer from low cooling flux. The situation becomes even deteriorated in the daytime when radiative coolers are exposed to direct sunlight. To tackle this challenge, an idea of employing both a spectrally selective cover and a spectrally selective emitter is proposed in this study as an alternative approach. A comparative study is conducted among four RC modules with different spectral characteristics for the demonstration of how the spectral profiles of the cover and the emitter affects the RC performance. The results under given conditions show that the RC module with a spectrally selective cover and a spectrally selective emitter (SC/SE) reaches a net RC power of 62.4 W/m^2 when the solar radiation is 800 W/m^2, which is about 1.8 times that of the typical RC module with a spectrally non-selective cover and a spectrally selective emitter (n-SC/SE). When the ambient temperature is 30 °C, the SC/SE based RC module realizes a daytime sub-ambient temperature reduction of 20.0 °C, standing for a further temperature decrement of 9.2 °C compared to the n-SC/SE based RC module.

1. Introduction

Radiative cooling (RC) is a completely passive cooling technology that attracts increasing attention in the research community [1]. An RC module mainly reaches a sub-ambient state by dissipating heat to the deep outer space via the well-known “atmospheric window (8–13 μm)” [2]. RC is a phenomenon widely existing in nature. For example, RC process is attributed to the surface frosting of grasses and leaves in later autumn and the surface water freezing in a still lake in winter even though the local ambient air is above the freezing temperature. Any real-world object can radiate heat to the surroundings and meanwhile receives heat from the outside environment according to the fundamental of heat transfer [3]. Therefore, if the outward radiative heat flux is greater than the inward absorbed heat flux, a net RC effect is produced.

RC technology has great potential to be applied in the building sector due to its structural simplicity and environmental friendliness [4,5]. By combining RC collectors that consume no or negligible energy with building envelops, a portion of building energy demand can be covered by the building-integrated RC system in a renewable and green manner. According to the architectural configuration, the RC module can generally be installed either on the facade [6,7], or the flat roof [8,9], or the pitched roof [10], especially on the non-sunward facing roof where solar radiation usually remains at low levels and thus making possible the daytime RC even with materials showing not extremely high solar reflectance [11]. Generally, the building-integrated RC system can either be designed as a passive or an active system. A passive RC system such as a cool roof usually delivers coldness to the indoor space through buoyancy-driven or reduces heat gain to the building mass by strongly rejecting solar. radiation and radiating waste heat simultaneously, but suffer from lower cooling performance and undesired cooling gain in cold seasons [9]. By contrast, an active RC system supplies cooling energy to the indoor environment in a more effective way through a driving unit such as a water pump or a draft fan which consumes a small amount of external energy [12]. The active RC system shows a higher cooling capacity compared to the passive system and matches with the seasonal energy demand better in buildings, but also bring unfortunate side effect of adding complexity and operating cost to the system.

RC performance is highly influenced by local environmental conditions. In general, a radiative cooler will reach a lower stagnation temperature or offer a greater RC flux in an environment with lower relative humidity [13], less cloud coverage [14], higher altitude [15], and lower solar intensity (for daytime RC application scenarios) [16]. Exper-

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Nomenclature

d	distance/thickness, m;
ρ	reflectance, -;
E	radiation power, W/m2;
σ	Stefan–Boltzmann constant, -;
G	solar radiation, W/m2;
λ	wavelength, μm;
h	heat transfer coefficient, W/(m2·K);
β	inclination angle, rad;
k	thermal conductivity, W/(m·K);
θ	zenith angle, rad;
l	length, m;
τ	transmittance, -;
Nu	Nusselt number, -

Abbreviation and subscripts

Q	thermal power, W/m^2;
a	ambient air;
Ra	Rayleigh number, -;
c	cover;
U	Overall heat-transfer coefficient, W/(m^2·K);
conv	convection;
u	wind velocity, m/s;
e	emitter

Greek Symbols

rad	radiation;
$(\tau\alpha)$	Transmittance-absorptance product, -;
rad_net	net radiation;
ε	emissivity, -;
s	sky

imental studies have demonstrated that an RC module with a daytime cooling capacity in a quite arid region failed to realize the same effect under a circumstance where the air is extremely humid [17]. The RC performance will be deteriorated if the sky is cloudy, as a cloud is essentially a cluster of water droplets and/or ice crystals which will severely block the radiative heat transfer between the radiative cooler and the extremely cold outer space; under such situation RC mainly happens between the radiative cooler and the upper atmosphere where the temperature is a couple of degrees lower than the earthbound bodies but much higher than the deep universe. It is easy to understood that the RC performance of an RC module will benefit from higher altitude, as the higher the ground is, the thinner air becomes and thus the less the atmosphere radiates heat to the RC module and obstructs the upward thermal emission from the RC module. The solar radiation is the most sensitive factor which influences the RC performance. Basically, the RC power is one order lower than the intensity of solar radiation, hence a tiny addition of solar energy will cause a large increment of stagnation temperature or a great decrement of net RC power or even evanish the RC effect.

Considering that the above uncontrollable environmental parameters affect the RC performance to a large extent, one can sustain RC in an active way by regulating the spectral profiles of the RC module itself. Although RC technology had been restricted to nighttime application for many years, daytime radiative cooling (d-RC) has been realized in recent years due to the realize of radiative emitter with near-ideal spectral selectivity. In 2014, Fan's group [18] designed and prepared a spectrally selective photonic radiative cooler which shows extremely high solar reflectance and high emissivity in the "atmospheric window". The radiative cooler can be cooled to 4.9 °C below ambient temperature when exposed to direct sunlight exceeding 850 W/m^2. Fan et al.'s work [18] is widely seen as a milestone in the development of RC technology. Thereafter, RC saw rapid development towards scalization, high-efficiency, affordability, and reliability, etc. With the increasing advancement in regulating the spectral profile of the radiative emitter in micro- and nano-scales, RC has been involved in outdoor personal cooling [19,20], passive cooling of solar cells [21,22], and nighttime power generation [23,24], etc. Particularly, many researchers have attempted to enhance the RC capacity by optimizing the spectral selectivity of the radiative emitter in a easier, cheaper, and more scalable way [25–29]. For the realization of RC to the greatest extent, the emitter of an RC module should at least possess the highest possible emissivity in the "atmospheric window" to strongly dump long-wave radiative heat to the sky [30]. Meanwhile, the emitter shall exhibit the highest possible reflectance in other bands, allowing the emitter to reject radiative heat from the local environment and to reach the lowest possible stagnation temperature [31]. For radiative coolers that aim to effectively work during the daytime under a high-level incident solar radiation, in particular, the emitter is restricted to show a reflectance of around 95% or even more in the solar spectrum (0.2–3 μm) in order to reject the vast majority of solar radiation [18,32]. For spectrally selective nighttime radiative coolers, on the other hand, the emitter only has to show spectral selectivity in the middle- and far-infrared wavelengths, regardless of its spectral profile in the solar radiation band. d-RC is supposed to be more suitable for building energy saving of office and commercial buildings in which energy consumption mainly takes place during the daytime [33]. The spectral characteristic of the ideal d-RC emitter is shown in Fig. 1 (red line). The AM 1.5 (AM = air mass) solar spectrum is a widely adopted physical quantity in solar energy technologies and is defined as the spectral distribution of solar intensity projected onto the earth's surface with an incident angle of about 48.2 °C [34].

The relatively low power density of d-RC modules, compared to that of the vapor compression refrigerator, is the main barrier for its promotion to real-world applications [35]. Though scholars have successfully developed near-ideal d-RC emitters with solar reflectance greater than 95%, the d-RC module still suffers from low-level RC flux during the daytime and there is little space for further development of the emitter regarding sunlight rejection. Besides, even a 1% improvement of solar reflectance under such a big base figure may involve massive efforts. While the effect of spectral modification of the emitter is widely appreciated by researchers, the great impacts that can result from controlling the spectral property of the convection cover are frequently not considered to be too profitable. The cover in an RC module is mainly used to limit the convection cooling loss as the emitter approaches its stagnation temperature. The most common cover material employed in existing RC modules is the low-density polyethylene (LDPE) film which shows high transmittance throughout the concerned bands from solar spectrum to far-infrared region, that is, the LDPE film presents no spectral selectivity in these bands [36]. Therefore, an extra opportunity brings out by developing spectrally selective covers that match better with the spectral requirement of d-RC cover [37,38]. Equipping with a cover that shows high solar reflectance while high mid-infrared transmittance can boost the net RC cooling power of a typical d-RC device to nearly 100 W/m^2 [37]. Provided the cover works as a mid-infrared transparent solar absorber, the underneath radiative cooler can also be free from the exposure of sunlight and reach a deep sub-ambient temperature [38]. However, the cooling potential of a radiative cooler can be further enhanced by employing a cover with better spectral selectivity. As is shown in Fig. 1 (blue line), the ideal d-RC cover should show high transmittance within the "atmospheric window" to allow thermal radiation from the emitter to go through freely. Besides, the cover should show low transmittance (high reflectance) excluding the transparent window, especially in the solar spectrum for d-RC applications, indicating that the cover can act as a guardian rejector to rebound most of the solar radiation and only allow a small fraction of sunlight projecting onto the emitter which also shows strong solar reflectance. Preparing a spectrally selective cover that can simultaneously achieve high solar reflectance and long-wave transmittance is challenging but engineering accessible [39–41], especially with the booming development in micro- and

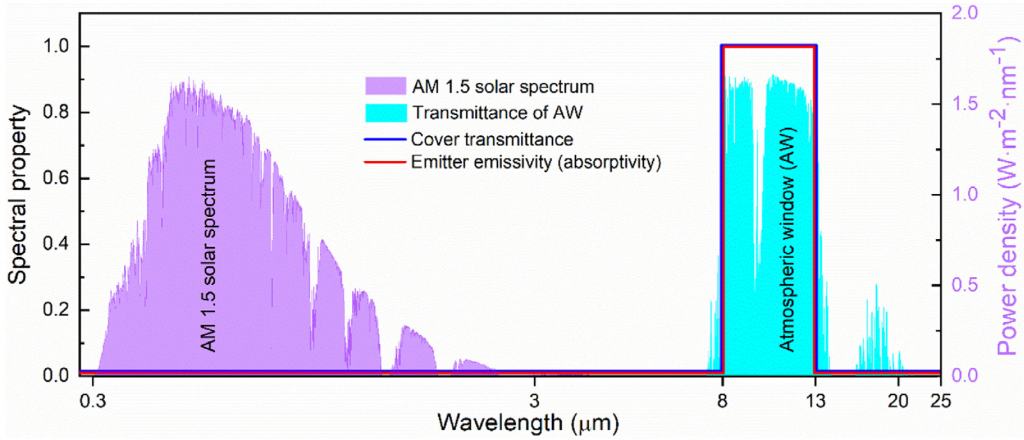

Fig. 1. Spectral characteristics of the ideal cover and emitter for daytime radiative cooling.

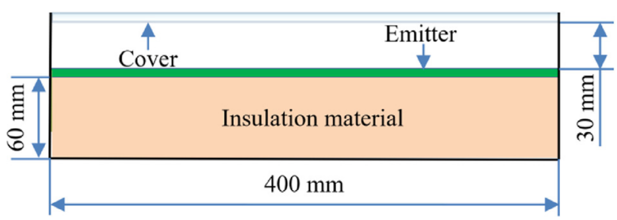

Fig. 2. Section structure of the radiative cooling module.

nano-material technologies. The cold mirror that has been widely applied in infrared instruments is a good candidate that meets the spectral selectivity of d-RC cover [42,43].

Though the effect of the spectral selectivity of the cover on the cooling performance of the radiative cooler has been experimentally demonstrated [37,38], a systematic parametric study can be further conducted to elucidate the underlying mechanisms of the spectral profile of the cover. In the present study, therefore, we quantificationally characterized the performance enhancement of the RC module equipped with a spectrally selective cover via heat transfer analysis. A mathematic model is developed for calculating the cooling performance of the RC module under different working conditions. Four RC modules, with different spectral profiles of the cover and emitter, is selected and compared with each other to demonstrate the effect of spectral selectivity on the key performance indicators, i.e., stagnation temperature and net RC power, of the modules.

2. Description of the RC module

The RC module present in this study is shown in Fig. 2 , which mainly includes a convection cover and an emitter, associated with some insulation materials below the emitter. The basic functions of the cover and insulations are suppressing convective and conductive cooling losses. The emitter of the RC module, with a dimension of 0.4×0.4 m, is placed horizontally to get the maximum view factor relative to the sky and thus get the best RC performance [44]. The vertical distance between the cover and the emitter is 0.03 m. A 60 mm-thick layer of phenolic foam, with a thermal conductivity of 0.028 W/(m·K) served as the insulation material.

According to the spectral profiles of the cover and emitter, four different RC modules is proposed as follows:

- The RC module with a spectrally non-Selective Cover and a non-Selective Emitter (n-SC/n-SE)
- The RC module with a spectrally non-Selective Cover and a Selective Emitter (n-SC/SE, the most common RC device in previous studies)

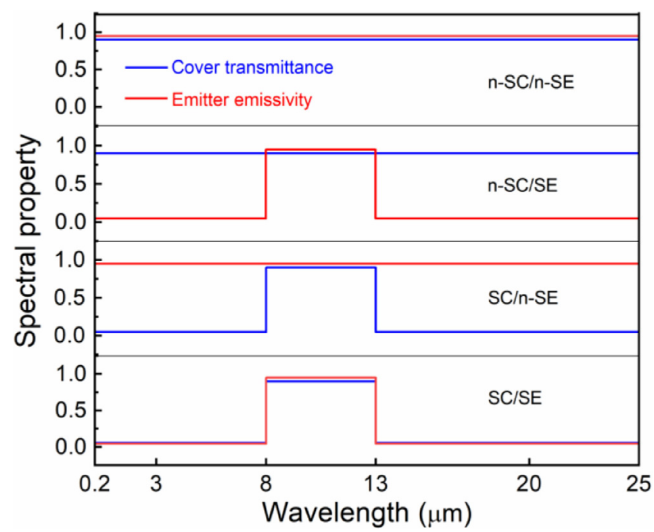

Fig. 3. The spectral profile of the cover and emitter of the four RC modules.

- The RC module with a spectrally Selective Cover and a non-Selective Emitter (SC/n-SE)
- The RC module with a spectrally Selective Cover and a Selective Emitter (SC/SE)

The spectral profile of the cover and emitter of the four RC modules are detailed in Table 1 and Fig. 3 . It is clear that the cover transmittance and emitter emissivity in the “atmospheric window” is 0.9 and 0.95 respectively for all the four RC modules as a base for the RC feature. The spectral difference among the four modules lies in other bands aside from the “atmospheric window” (hereafter referred to as the “other bands”). For those modules with a spectrally non-selective cover, the cover transmittance in the other bands is 0.9 but switch to 0.05 for those modules with a spectrally selective cover. For those modules with a spectrally non-selective emitter, the emitter emissivity in the other bands is 0.95 but switch to 0.05 for those modules with a spectrally selective emitter. The schematic diagram of the SC/SE based module is further shown in Fig. 4 .

3. Mathematic model

A steady-state mathematic model is developed for the characterization of the RC performance of the four modules. The following assumptions are adopted to simplify modeling and analysis [45]:

Table 1
The spectral profile of the cover and emitter of the four RC modules.

Spectral profile	n-SC/n-SE	n-SC/SE	SC/n-SE	SC/SE
Cover transmittance in the "atmospheric window" (α = 0.05)	0.9	0.9	0.9	0.9
Cover transmittance in the other bands (α = 0.05)	0.9	0.9	0.05	0.05
Emitter emissivity (absorptivity) in the "atmospheric window"	0.95	0.95	0.95	0.95
Emitter emissivity (absorptivity) in the other bands	0.95	0.05	0.95	0.05

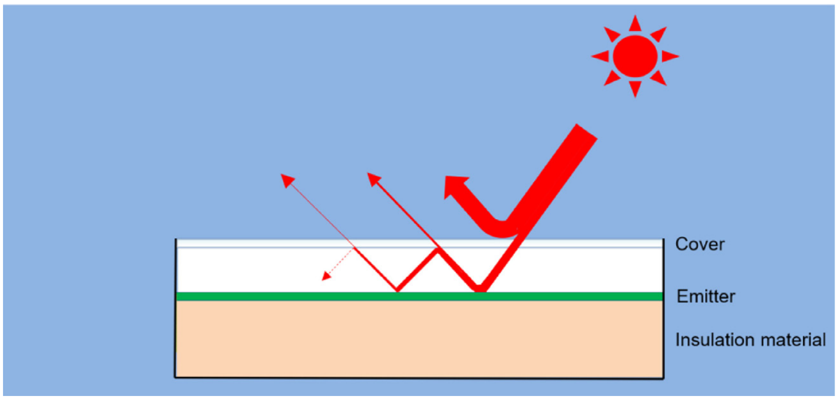

Fig. 4. Schematic diagram of the radiative cooling module equipped with a spectrally selective cover and emitter.

- The spectral properties of the cover and emitter are independent of temperature.
- The temperatures of the cover and emitter are independent of direction.
- The cover and emitter are considered as diffusers; thus, their spectral properties are independent of angle.
- The heat or cooling loss takes place along the four side edges of the RC module is negligible.

As the RC module mainly consists of two components, namely, the cover and the emitter, the mathematic model primarily comprises two main equation sets, namely, (i) energy-balance equation of the cover and (ii) energy-balance equation of the emitter.

3.1. Energy-balance equation of the cover

Take the cover as the control volume, it exchanges heat with the ambient air, the sky, the emitter, and absorbs solar energy from the sun. Therefore, the heat balance equation of the transparent cover is expressed as follows:

$$h_{ac}(T_a - T_c) + h_{sc}(T_s - T_c) + h_{ec}(T_e - T_c) + \alpha_c G = 0 \quad (1)$$

where h_{ac} and h_{sc} are respectively the convective and radiative heat transfer coefficients between the cover and the local environment, W/(m^2·K); h_{ec} is the heat transfer coefficient between the cover and the emitter, W/(m^2·K); T_a, T_c, T_s, and T_e are the temperatures of the ambient air, cover, sky, and emitter, respectively, K; α_c is the absorptivity of the cover in the solar spectrum; and G is the solar radiation, W/m^2.

The sky temperature is derived as follows [46]:

$$T_s = 0.0552 T_a^{1.5} \quad (2)$$

The convective and radiative heat transfer coefficients between the cover and the environment are calculated as Eqs. (3) and (4), respectively [47]:

$$h_{ac} = 2.8 + 3.0 u_a \quad (3)$$

and

$$h_{sc} = \varepsilon_c \sigma (T_s^2 + T_c^2)(T_s + T_c) \quad (4)$$

where u_a is the wind velocity, m/s; ε_c is the cover emissivity; and σ is the Stefan–Boltzmann constant.

The heat exchange between the cover and the emitter consists of two parts, i.e., heat convection and heat radiation. The heat transfer coefficient can be calculated as follows:

$$h_{ec} = h_{ec\_conv} + h_{ec\_rad} \quad (5)$$

The convective heat transfer coefficient between the cover and the emitter is written as follows [3]:

$$h_{ec\_conv} = \frac{Nu \cdot k_a}{d_{ec}} \quad (6)$$

where Nu is the Nusselt number; k_a is the thermal conductivity of air between the cover and the emitter, W/(m·K); and d_{ec} is the vertical distance of the air gap, m.

For a rectangular enclosure with inclination angles ranging from 0° to 75°, if $T_e > T_c$, then the Nusselt number can be calculated as follows [3]:

$$Nu = 1 + 1.44\left(1 - \frac{1708 \cdot (\sin 1.8\beta)^{1.6}}{Ra \cdot \cos\beta}\right)\left[1 - \frac{1708}{Ra \cdot \cos\beta}\right]^{+} + \left[\left(\frac{Ra \cdot \cos\beta}{5830}\right)^{1/3} - 1\right]^{+} \quad (7)$$

where the + exponent indicates that only positive values are used for terms within the square brackets; in case of negative values, zero is used; β is the inclination angle of the collector, rad; and Ra is the Rayleigh number.

If $T_e < T_c$, then the Nusselt number is expressed as follows [48]:

$$Nu = 1 + \left[0.364 \frac{l_e}{d_{ec}} Ra^{1/4} - 1\right] \sin\beta \quad (8)$$

where l_e is the length of the emitter, m.

If $T_e = T_c$, then no heat convection occurred between the cover and the emitter. Therefore, the Nusselt number is equal to zero.

The radiative heat transfer coefficient between the cover and the emitter, considering the transmittance of the cover and the multiple-reflections between the two components, is derived as follows [45]:

$$h_{ec\_rad} = \frac{\alpha_c \varepsilon_e \sigma T_e^4 - \alpha_e \varepsilon_c \sigma T_c^4}{(1 - \rho_c \rho_e) \cdot (T_e - T_c)} \quad (9)$$

where ε_e is the emitter emissivity; α_c and α_e are respectively the absorptivity of the cover and the emitter; ρ_c and ρ_e are the reflectance of the cover and the emitter, respectively.

3.2. Energy-balance equation of the emitter

Take the emitter as the control volume, it exchanges heat with the cover, the sky, the hypothetical backside working medium, and with the ambient air through the backside thermal insulation, as well as absorbs solar energy from the sun. Therefore, the heat balance equation of the collecting surface is expressed as follows:

$$U_{ae}\left(T_a - T_e\right) + h_{ec}\left(T_c - T_e\right) + (\tau\alpha)_e G - Q_{rad\_net} \pm Q_{output} = 0 \quad (10)$$

where U_{ae} is the overall heat transfer coefficient between the emitter and the local environment, W/(m^2·K); $(\tau\alpha)_e$ is the effective transmittance–absorptance product of the RC module; Q_{rad_net} is the net radiative power of the emitter, W/m^2; Q_{output} is the heat ("-" sign) or cooling energy ("+" sign) extracted from the emitter in order to maintain the emitter at a set temperature, W/m^2. Obviously, Q_{output} will turn to zero if the emitter reaches its stagnation temperature.

The backside thermal insulation and the backboard are two thermal barriers between the emitter and ambient air. The heat convective coefficient between the backboard and ambient air is equal to that between the cover and ambient air since the backboard and cover are both in flat-plate structures. Therefore, the overall heat transfer coefficient between the emitter and the local environment is calculated as follows [49]:

$$U_{ae} = \frac{1}{\frac{1}{h_{ac}} + \frac{d_b}{k_b}} \quad (11)$$

where d_b is the thickness of the back insulator, m; and k_b is the thermal conductivity of the back insulator, W/(m·K).

The effective transmittance–absorptance product of the module is derived as follows [46]:

$$(\tau\alpha)_e = \frac{\tau_c \alpha_e}{1 - \left(1 - \alpha_e\right)\rho_c} \quad (12)$$

where α_e is the absorptivity of the emitter; and τ_c and ρ_c are respectively the transmittance and reflectance of the cover.

The net radiative power of the emitter is written as follows:

$$Q_{rad\_net} = Q_{rad\_e} - Q_{rad\_se}. \quad (13)$$

The outward radiation of the emitter (Q_{rad_e}) is computed as follows [50]:

$$Q_{rad\_e} = \int_0^\infty \left[\frac{E_{b,\lambda}\left(T_e\right)\cdot\left(1-\rho_{c,\lambda}\right) - \varepsilon_{c,\lambda}\cdot E_{b,\lambda}\left(T_c\right)}{1/\varepsilon_{e,\lambda} - \left(\left(1-\varepsilon_{e,\lambda}\right)/\varepsilon_{e,\lambda}\right)\cdot\rho_{c,\lambda}}\right] d\lambda \quad (14)$$

where $E_{b,\lambda}$ is the spectral radiation power of the blackbody, W/(m^2•μm); $\rho_{c,\lambda}$ and $\varepsilon_{c,\lambda}$ are respectively the spectral reflectance and emissivity of the cover; and $\varepsilon_{e,\lambda}$ is the spectral emissivity of the emitter.

The radiation from the sky to the emitter Q_{rad_se} is expressed as follows [50]:

$$Q_{rad\_se} = 2\int_0^\infty \int_0^{\pi/2} \varepsilon_{s,\lambda}(\lambda,\theta)\cdot E_{b,\lambda}\left(\lambda, T_a\right)\cdot \alpha_{e,\lambda}(\lambda,\theta) \times \tau_{c,\lambda}(\lambda,\theta)\sin\theta\cos\theta d\theta d\lambda \quad (15)$$

where $\varepsilon_{s,\lambda}$ and $\tau_{c,\lambda}$ are respectively the spectral emissivity of the sky and transmittance of the cover; and θ is the zenith angle, rad.

The mathematic model was experimentally validated in a previous work focused on the thermal analysis of a combined photovoltaic–photothermic–nocturnal radiative cooling (PV-PT-RC) module [50]. A favorable consistency was observed between the experimental and simulated stagnation temperatures of the PV-PT-RC module. The geometric structure of the PV-PT-RC module is similar to that of the present RC module and hence the simulation results of this study are convincing.

4. Results and discussion

Based on the mathematic model developed in Section 3, we conduct an extensive investigation on the performance of the four RC modules under different working conditions. Standard operating conditions are set before the simulation study, as listed in Table 2.

Table 2
Standard operating conditions for the RC module.

Parameter	Value
Wind velocity (m/s)	2
Ambient temperature (°C)	30
Relative humidity (%)	50
Solar radiation (W/m^2)	800 (daytime) or 0 (nighttime)

4.1. RC performance in daytime

Fig. 5 illustrates the performance of the four typical RC modules during the daytime exposed to the sunlight directly with solar radiation of 800 W/m^2. Different from the other three modules, the n-SC/n-SE based module cannot achieve a d-RC effect in such a case. In fact, it shows quite good solar heating performance during the daytime. Specifically, its net solar heating power reaches around 605.1 W/m^2 at zero-reduced temperature (when the emitter temperature equals the ambient temperature) and its stagnation temperature records about 92.6 °C. As the emitter shows a high absorptivity of 0.95 in the solar spectrum and the cover allows 90% of solar radiation to get through, most of the incident solar energy is absorbed and then is dissipated into thermal energy which, in turn, heats up the emitter of the n-SC/n-SE based module. On the other hand, due to the high emissivity (0.95) in those bands outside the solar spectrum, the n-SC/n-SE based module loses a part of long-wave thermal emission and thus is expected to be inferior in thermal efficiency than the typical solar thermal collector which is usually equipped with solar selective absorbing coatings.

The other three modules, by contrast, show d-RC capacities and the same changing trend as the emitter temperature increases. The cooling performance of the n-SC/SE based and SC/n-SE based modules are rather close. Their net RC power is respectively 35.7 and 33.8 W/m^2 and their stagnation temperature is 19.2 and 19.8 °C, respectively. It is indicated that, therefore, the approach that adopts a spectrally non-selective emitter but a spectrally selective cover can be treated as an alternative to the typical solution of employing a spectrally selective emitter but a spectrally non-selective cover. This makes sense indeed for those situations the emitter has to show high emissivity outside the "atmospheric window" for other purposes but also has a demand for d-RC. It is also clear from Fig. 5 that, by fully taking advantage of the benefit from spectral selective cover and spectrally emitter together, the SC/SE based module presents much better cooling performance than the n-SC/SE and SC/n-SE based modules in such a daytime working condition with strong solar intensity. In specific, the SC/SE based module can realize a stagnation temperature of approximately 10.0 °C, achieving a further temperature reduction of 9.2 °C compared to the typical n-SC/SE based module. Besides, the net RC power of the SC/SE based module reaches about 62.4 W/m^2, indicating that a performance improvement of 74.8% is observed in this case. Therefore, applying the SC/SE based structure offers a potential strategy for mitigating the challenge of improving RC density. It is admitted that achieving a near-perfect spectrally selective cover is challenging. However, referring to the development route of high-performing radiative emitter over the past few years, it is conceivable to realize the desired spectrally selective cover in the near future.

4.2. RC performance in nighttime

Along with the investigation of the four typical modules working in daytime conditions, we also evaluated their performance in the nighttime case. As shown in Fig. 6, the cooling power of all the four modules decline almost linearly as the emitter temperature decreases. Unlike the situation in the daytime, the net RC flux of the n-SC/n-SE based module is even slightly greater than the rest of RC modules in the nighttime, with the value approaches 83.9 W/m^2. This is because the high emissivity in the other bands also promotes the cooling performance

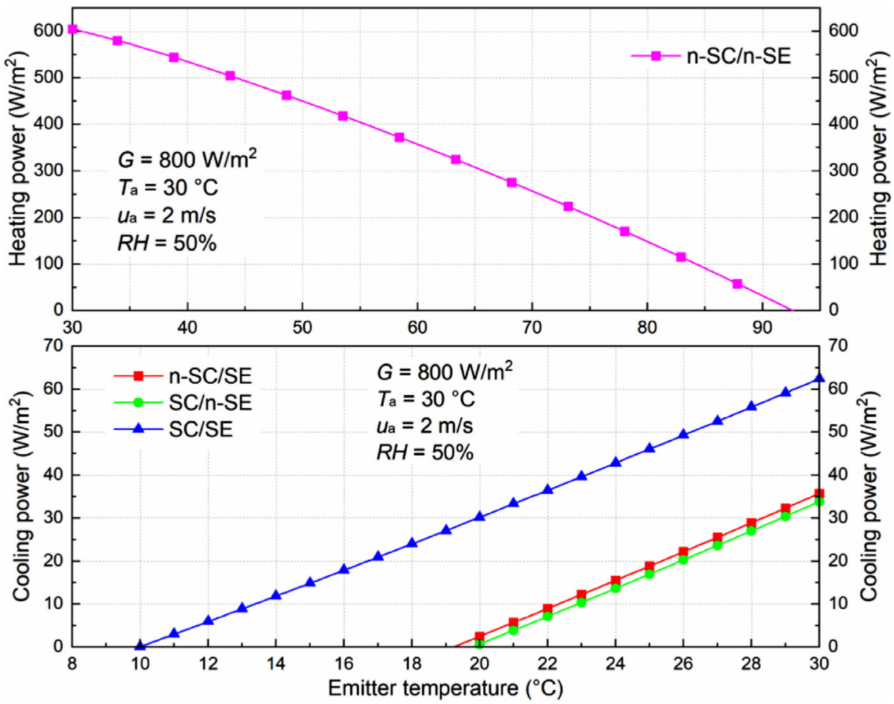

Fig. 5. Performance of the four RC modules in a daytime condition.

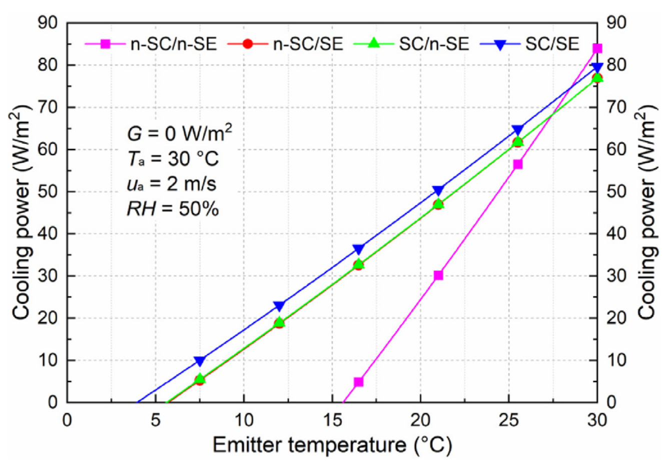

Fig. 6. Performance of the four RC modules in a nighttime condition.

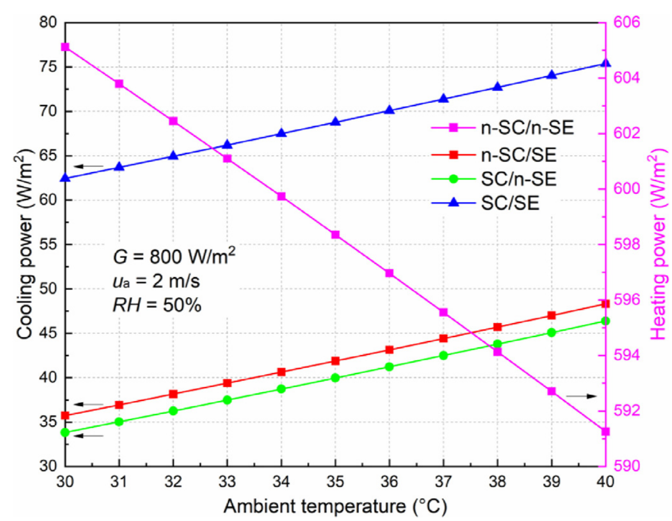

Fig. 7. Performance of the four RC modules at different ambient temperatures.

by realizing a net inward cooling flux when the emitter temperature is higher than a certain level which depends on certain conditions. In the present study, for example, the cooling density of the n-SC/n-SE based module is greater than the n-SC/SE based and SC/n-SE based modules when the emitter temperature is higher than 27.4 °C and is superior to the SC/SE based module when the emitter temperature is higher than 28.5 °C. However, the cooling power of the n-SC/n-SE based module declines much faster than that of the rest three modules as the emitter temperature decreases, resulting in a much higher stagnation temperature. In this study, the nighttime stagnation temperature of the n-SC/n-SE based module is 15.6 °C, which is over 10 °C higher than that of the n-SC/SE based, SC/n-SE based, and SC/SE based modules. Considering that the n-SC/n-SE based module also shows a good daytime solar heating capacity, as demonstrated in Section 4.1, it has the potential to be a dual-functional collector and provide both heat and cooling energy for buildings [35].

The changing curve of the cooling power for the n-SC/SE based and SC/n-SE based modules is nearly overlapped in nighttime working conditions, indicating that their nocturnal cooling performance is more or less the same. Their net RC power and stagnation temperature are about 77.0 W/m^2 and 5.6 °C, respectively. Distinct from the case in the daytime, the cooling performance improvement by employing the SC/SE based structure is not that much in the nighttime condition. Compared to the typical n-SC/SE based module, the net RC flux of the SC/SE based module only increases relatively by 3.5%, and a further stagnation temperature reduction of only 1.8 °C is observed. Therefore, for the nighttime RC application, it may not make much sense to equip the module with both spectrally selective cover and emitter. It is more feasible to employ only a spectrally selective cover or a spectrally selective emitter considering the preparation cost.

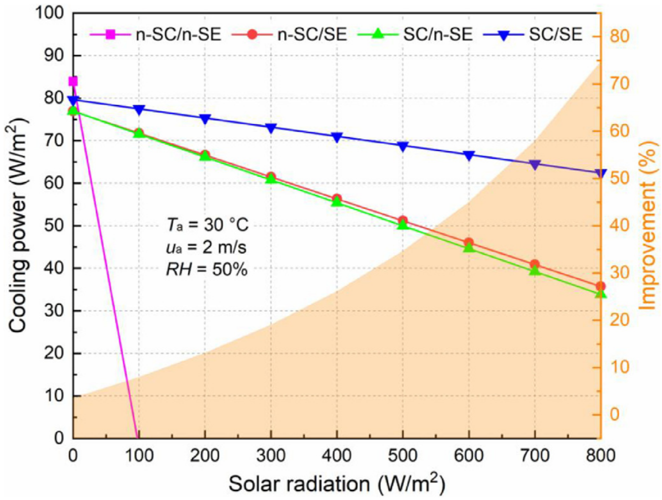

Fig. 8. Performance of the four RC modules under different solar radiation.

4.3. RC performance under different ambient temperatures

Cooling energy is more required in high-temperature weather. Therefore, we also assessed the RC performance of the four modules in an extended range of high ambient temperatures, and the results are shown in Fig. 7 . Higher ambient temperature leads to higher emitter temperature and thus greater outward thermal emission of the emitter. As the solar radiation is set at 800 W/m^2, the n-SC/n-SE based module cannot achieve the cooling effect and its net solar heating power decreases gradually from 605.1 to 591.3 W/m^2 as the ambient temperature increases from 30 to 40 °C. In contrast, the other three modules exhibit enhanced cooling performance as the ambient temperature increases. The SC/SE based module still shows the best cooling behavior among the four modules, with the net RC power increases from 62.4 to 75.4 W/m^2 as the ambient temperature elevates from 30 to 40 °C. The n-SC/SE and SC/n-SE based modules exhibit close net RC power, with the values being about 35 and 47 W/m^2 when the ambient temperature is respectively 30 and 40 °C.

4.4. RC performance under different solar radiation

As the solar intensity is a key factor that affects the cooling performance of the RC module in the daytime. We further studied the cooling performance of the four modules under different solar radiation, and the results are shown in Fig. 8 . The cooling performance of the n-SC/n-SE based module is very sensitive to the solar intensity, with the cooling power descends sharply from 83.9 to 0 W/m^2 as the solar radiation increases from 0 to around 100 W/m^2, indicating that the n-SC/n-SE based module is unable to realized RC effect in most daytime situations. The

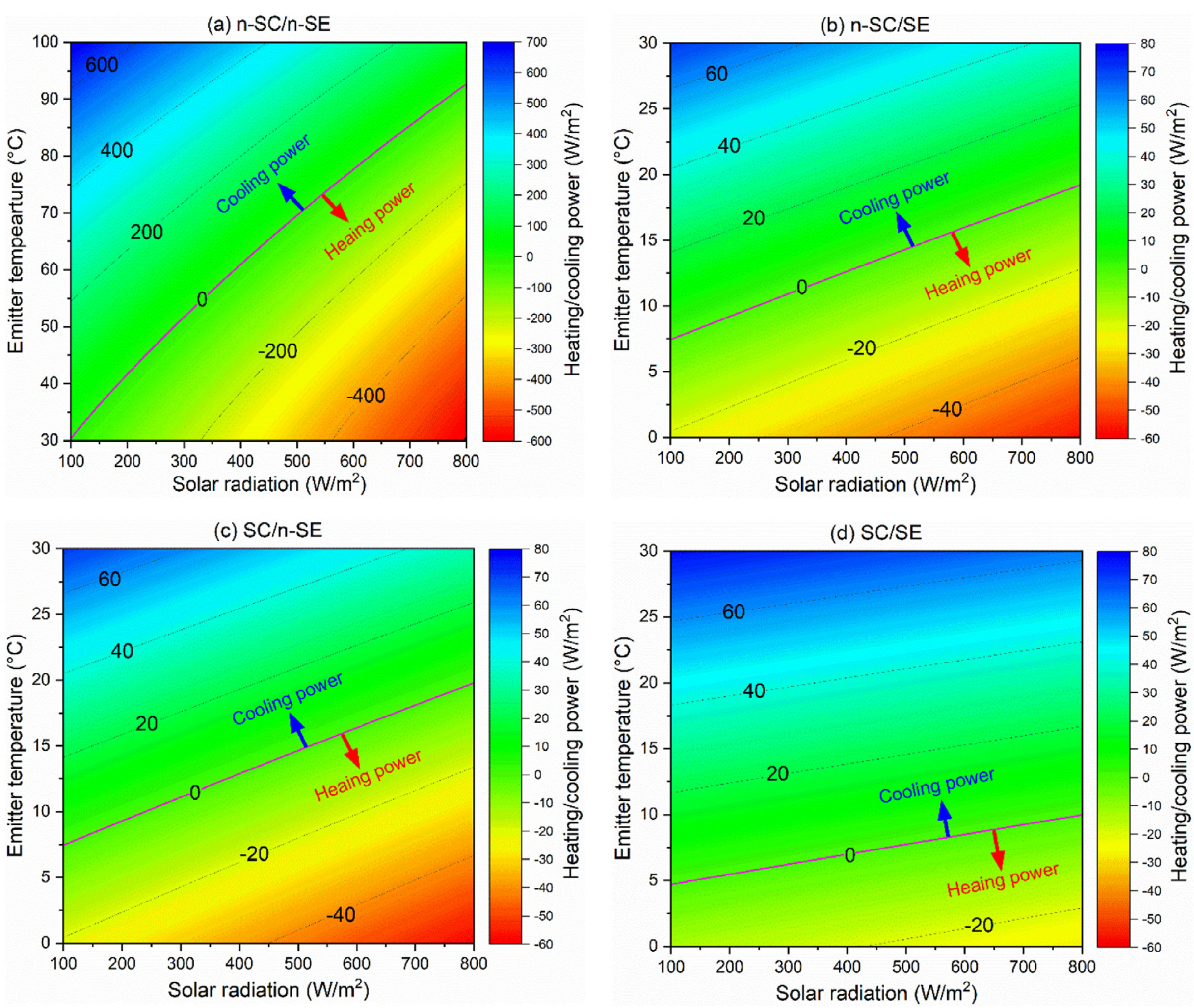

Fig. 9. Coupling effect of emitter temperature and solar radiation on the performance of the four modules at the ambient temperature of 30 °C.

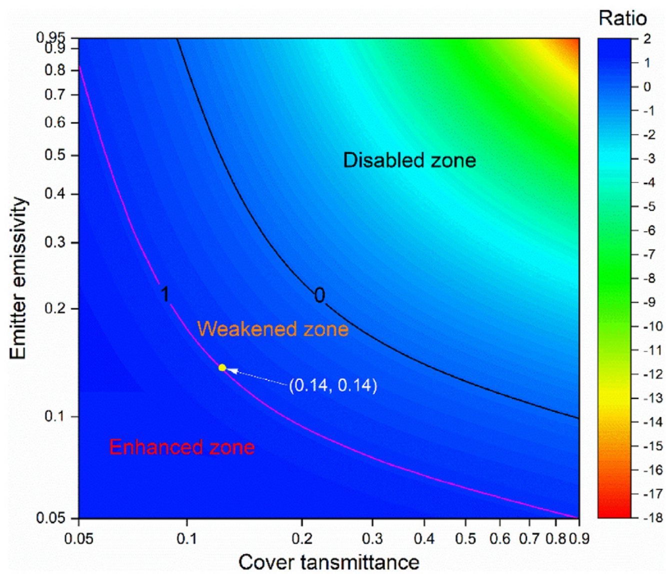

Fig. 10. The cooling capacity of the SC/SE based module with different spectral profiles (relative to the cooling performance of the n-SC/SE based module).

cooling power of the n-SC/SE based module is getting greater than that of the SC/n-SE based module as the solar radiation increases, but the gap is tiny even at a very high solar intensity of 800 W/m^2. The SC/SE based module is the least sensitive to the solar radiation regarding cooling performance, with the cooling power decreases gradually from 79.7 to 62.4 W/m^2 as the solar radiation goes up from 0 to 800 W/m^2. Besides, as the solar radiation increases, the superiority of the SC/SE based module in terms of cooling performance comparing the typical n-SC/SE based module magnifies. As is shown in Fig. 8, the cooling power improvement rises from 3.5% to 74.7% as the solar radiation increases from 0 to 800 W/m^2.

4.5. Coupling effects of emitter temperature and solar radiation

Emitter temperature is another key parameter, in addition to solar radiation, that affects the cooling performance. In this section, therefore, we examined the coupling effect of emitter temperature and solar radiation on the performance of the four modules, as the results presented in Fig. 9. It is clear from the contour plots that greater cooling power will be gained at higher emitter temperature and lower solar radiation for all the four modules. As illustrated in Fig. 9(a), the n-SC/n-SE based module cannot achieve a sub-ambient d-RC effect as the solar radiation is greater than 100 W/m^2. The contour plots of the n-SC/SE based and SC/n-SE based modules are quite similar, with the sub-ambient d-RC effect can be realized in nearly half of the situations. By contrast, the SC/SE based module can reach a sub-ambient d-RC effect in most situations, except in those the emitter temperature is extremely low or the solar radiation is rather higher, further demonstrating that the SC/SE based module is more suitable for d-RC application scenarios.

4.6. Compromised strategy to daytime radiative cooling for the SC/SE based module

As demonstrated in the above Sections, the SC/SE based module shows much better cooling performance than the n-SC/SE based structure that is widely adopted in reported studies, but it may be the case in real-world applications that achieving near-perfect spectral properties for the cover and the emitter simultaneously is laboursome and costly. But from another point of view, the SC/SE idea provides a compromised strategy to realize effective d-RC by using not very elaborated cover and emitter. Fig. 10 illustrates the cooling capacity of the SC/SE based module with different spectral profiles under solar radiation of 800 W/m^2 by comparing it to the cooling power of the n-SC/SE based module. The contour plot is divided into three zones, namely, disabled zone, weakened zone, and enhanced zone. The words “disabled zone” signifies that in this area the SC/SE based module is unable to achieve d-RC in such an environmental condition due to the poor spectral selectivity of both the cover and the emitter. In the weakened zone, the SC/SE based module can realize d-RC but its performance is inferior to the n-SC/SE based module with a near-perfect emitter regarding spectral selectivity. The emphasis lies in the enhanced zone as the SC/SE based module shows better d-RC performance than the n-SC/SE based module in this section. The larger the enhanced zone is, the more leeway leaves for compromises regarding the spectral selective of the cover and the emitter. While the n-SC/SE based module requires an emitter that reflects around 95% of solar radiation, the SC/SE based module can reach a same cooling performance by, for example, employing an easily engineered emitter that reflects only 86% of solar radiation (α = 0.14), associated with a cover that shows solar transmittance of 0.14.

5. Conclusions

In the present work, four different types of RC modules with individual spectral profiles are proposed to demonstrate the effect of spectral selectivity on the RC performance under different environmental conditions. A mathematic model is developed to conduct the simulation analysis and help to draw the following main findings:

(1) The n-SC/n-SE based module cannot achieve d-RC in most of the daytime situations but has the potential to be a dual-functional collector for daytime heating and nighttime cooling.
(2) The SC/SE based module shows a net RC power which is 1.8 times that of the typical n-SC/SE based module in a daytime working case, but the nocturnal performance enhancement by applying the SC/SE based structure is not distinct.
(3) The SC/SE based module can reach the sub-ambient d-RC effect in most situations, except in those the emitter temperature is extremely low or the solar radiation is rather higher.
(4) The SC/SE based structure offers an opportunity to achieve d-RC by employing devices equipped with moderate spectrally selective cover and emitter.

Overall, the idea of using spectrally selective cover and emitter together contributes an alternative strategy to alleviate the challenge of effectively running d-RC devices in real-world applications. Further researches should attach primary importance to potential cover materials with fitted spectral selectivity, as well as mechanical strength weather fastness.

Declaration of Competing Interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, “**Effect of the spectrally selective features of the cover and emitter combination on radiative cooling performance**”.
Authors

CRediT authorship contribution statement

Mingke Hu: Methodology, Software, Formal analysis, Investigation, Funding acquisition, Writing - original draft, Writing - review & editing. **Suhendri:** Software, Formal analysis, Writing - review & editing. **Bin Zhao:** Methodology, Formal analysis, Writing - review & editing.

Xianze Ao: Formal analysis, Writing - review & editing. **Jingyu Cao:** Formal analysis, Funding acquisition. **Qiliang Wang:** Formal analysis. **Saffa Riffat:** Resources, Project administration, Supervision. **Yuehong Su:** Supervision, Project administration, Funding acquisition, Writing - review & editing. **Gang Pei:** Conceptualization, Resources, Supervision, Project administration, Funding acquisition.

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