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Research Paper

Numerical study and experimental validation of a combined diurnal solar heating and nocturnal radiative cooling collector

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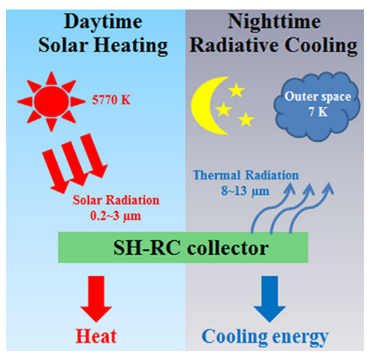
HIGHLIGHTS

- A collector to achieve both diurnal solar heating and nocturnal radiative cooling.
- A thermal model was established and experimentally validated.
- Spectral radiant and spatial temperature distributions were considered in the model.
- Precipitable water vapor amount was used to predict the spectral emissivity of sky.
- Parametric and annual simulations were conducted to evaluate the thermal performance.

GRAPHICAL ABSTRACT



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ABSTRACT

Neither solar collectors nor nocturnal radiative cooling units could work all day. A novel combined diurnal solar heating and nocturnal radiative cooling (SH-RC) collector was proposed and investigated in this study. The collector can obtain heat at daytime and gather cooling energy at nighttime, therefore offering multi-functionality and enhancing its time utilization ratio. A spatial distributed parameter mathematic model that considers the spectral radiant distribution was established to evaluate the performance of the collector. Besides, the precipitable water vapor amount was introduced to predict the spectral emissivity of atmosphere. Experiments were conducted to validate results obtained from the numerical simulation. The root-mean-square deviations between the experimental and simulation results are only 4.59% for thermal efficiency and 4.90% for cooling power. Based on the validated models, the thermal performance of the collector was investigated under different insulation thicknesses, wind velocities, ambient and inlet temperatures, water flow rates, precipitable water vapor amounts and solar irradiance. Annual performances of four Chinese cities were also conducted. The annual heat gains of the SH-RC collector in Beijing, Hefei, Fuzhou and Urumqi are 3328.76, 2423.53, 2543.31 and 3313.46 MJ/m^2, respectively. The annual net radiative cooling gains of the collector in the four cities are 862.44, 831.54, 741.63 and 775.34 MJ/m^2, respectively.

1. Introduction

In recent decades, the increasing energy crisis and environmental pollution have drawn greater attention to promote renewable energy technologies for energy sustainability worldwide [1]. Solar energy is treated as a promising alternative energy source to achieve energy

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Nomenclature

A_c	collector area, m^2
a_0, a_1, a_2, a_3	fitting coefficients, –
c	specific heat capacity, J/(kg·K)
D	diameter, m
d	distance/thickness, m
E	radiation power, W/m^2
G	solar irradiance, W/m^2
h	heat transfer coefficient, $W/(m^2{\cdot}K)$
k	thermal conductivity, W/(m·K)
L	length, m
$\dot{m}$	mass flow rate, kg/s
Nu	Nusselt number, –
Q	thermal power, W/m^2
R	thermal resistance, K/W
Ra	Rayleigh number, –
T	temperature, K
t_d	dew point temperature, °C
U	overall heat-transfer coefficient, $W/(m^2{\cdot}K)$
u	wind velocity, m/s
w	precipitable water vapor amount, cm

Greek symbols

τ	transmittance, –
$(\tau\alpha)$	transmittance-absorptance product, –
α	absorptivity, –
ε	emissivity, –
ρ	reflectance, –
σ	Stefan–Boltzmann constant, –
λ	wavelength, μm
β	inclination angle, rad
θ	radiation angle, rad
φ	inclination angle factor, –

Abbreviation and subscripts

a	ambient air
b	insulation backing plate
c	transparent cover
conv	convection
exp	experiment
f	working fluid
i	inner
o	outer
p	collecting plate
rad_net	net radiation
rad_p	radiated by collecting plate
rad_s	radiated by sky
s	sky
sim	simulation
t	copper tube

conservation and environment protection [2–4]. Solar heating technologies are the most developed solar energy applications nowadays [5–10]. The largest proportion of energy consumed by buildings come from space heating and cooling, which now occupies a significant share of society's total energy consumption [11]. Solar energy installations, especially flat plate solar collector (FPC) can be integrated with building envelopes easily and can significantly reduce building energy consumption, thus attracting many researchers to promote this technology [12,13]. The collecting plate is the key component of the FPC. To collect as much solar energy as possible, high solar absorptivity and low heating loss must be ensured. Therefore, the collecting plate should show obvious spectrally selectivity in solar radiation band (0.2–3 μm) and long-wave radiation wavelength (above 3 μm), namely, the collector plate should possess high spectral absorptivity in the solar radiation band and low spectral emissivity in the long-wave radiation band [14]. Solar selective absorbing coatings meet the above requirements, and thus, have been widely used on the FPC since Tabor introduced the concept in 1950s [15]. Terrestrial infrared radiation mainly focuses around 10 μm according to the Wien's displacement law [16]. Coincidently, the atmosphere possesses extremely high transmittance in wavelengths ranging between 8 μm and 13 μm (i.e., atmospheric window) [17–20]. Therefore, Objects on the Earth's surface, usually at nighttime, can obtain a cooling power by radiating heat to the cold outer space through the atmospheric window. This so called long-wave nocturnal radiative cooling is another promising technology for energy saving and emission reduction on account of its ability to gather cooling power without any external driving energy input. A radiative cooling collector is usually made into flat plate structure as well [21–23]. Radiative cooling is a green technology that attracts an increasing number of researchers to promote it. Radiative cooling is proved to be an effective way to lower the operating temperature of PV cells and thus improves the photovoltaic efficiency [24,25]. This passive cooling approach is also been widely applied in building energy saving [17,19,26,27]. One of the main barriers to more extensive application of radiative cooling is the weatherability of the transparent cover. Bathgate and Bosi manufactured a Zinc sulphide cover to be a durable substance suitable for the transparent cover for radiative cooler [28]. Gentle et al proposed a polyethylene mesh cover to achieve a long outdoor lifetime [29].

The flat plate solar collector and radiative cooling collector have their own limitations. Given the absence of solar irradiation during the nighttime, as well as the spectral property of its collecting plate and glazing cover, The FPC can solely provide heating function in the presence of sunlight and remains idle at nighttime. When it comes to the radiative cooling collector, though lots of productive work have made recently to achieve daytime radiative cooling [18,30–32], the device cannot easily and economically obtain cooling effect when being exposed to the sunlight at daytime because of its low cooling power density and stringent requirement on the local weather [17,33]. Since the FPC and nocturnal radiative cooling collector operate at opposite time period and provide opposite function, while have the similar components such as the cover, collecting plate, insulation material and frame. If nocturnal radiative cooling can be integrated with diurnal solar heating into a single unit using same components, the initial cost of this hybrid collector will be reduced significantly. What is more, this collector can provide heat energy at daytime and cooling energy at nighttime to achieve a multi-functional and all day operation. To conduct diurnal solar heating and nocturnal radiative cooling on the same collector, a spectrally selective collecting plate that can achieve the two functions should be obtained. This specific collecting plate should exhibit high spectral absorptivity (emissivity) in both solar radiation and atmospheric window bands so that it could obtain a favorable heating efficiency during daytime and a large cooling power at nighttime. Furthermore, the plate should exhibit low spectral absorptivity (emissivity) in other bands aside from solar radiation and atmospheric window wavelengths, allowing it to reduce daily radiant heating loss and nightly radiant cooling loss when exchanging heat with the sky and the surroundings. The spectral property of ideal collecting plate for both solar heating and radiative cooling is shown in Fig. 1 [34]. Besides, the cover of this combined collector should have high spectral transmittance in solar radiation and atmospheric window wavelengths, which enables most radiation in the two regions to go through it. The