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Parametric analysis and annual performance evaluation of an air-based integrated solar heating and radiative cooling collector

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ABSTRACT

Given the disadvantaged seasonal adaptability of solar air heaters and radiative air coolers, this study proposed an air-based integrated solar heating (SH) and radiative cooling (RC) collector (SH–RC collector). Such dual-function collector is capable of obtaining heat in SH mode and gaining cooling energy in RC mode. Accordingly, an air-based SH–RC collector can offer hot air during cold and harvest seasons and provide cool air during hot seasons. A spectrally selective plate termed as TPET collecting plate was trial-manufactured, serving as the panel of the air-based SH–RC collector. Also, this study developed a mathematical model and investigated the SH and RC performances of the proposed collector on a fine summer day. As the results suggest, the average thermal efficiency of the collector in SH mode reaches 45.88%, and the average cooling power of the collector is 36.61 W/m^2. Parametric studies on the effect of various ambient temperatures, inlet air temperatures, air flow rates, relative humidity values, and wind velocities on the SH and RC performances of the collector have been conducted. In addition, the monthly energy gains of the air-based SH–RC collector were calculated. The annual heat and cooling gains of the SH–RC collector reached 2328.45 and 980.43 MJ, respectively.

1. Introduction

Flat-plate solar air collector is one of the most developed solar energy applications; which has been broadly applied in space heating [1] and crop drying [2,3]. Though the solar air collector is somehow inefficient in comparison with the solar water heater [4], it is advantaged in its simple mechanism, low cost as well as long lifespan [5,6]. Besides, when or where solar water collectors may be inoperable, the solar air collector can effectively continue to run in freezing seasons and regions [6]. Previous investigations have primarily focused on increasing the thermal efficiency of the solar air collector. By pursuing the highest possible absorptivity in the solar radiation band (0.2–3 μm; abbreviated as the "SH band") and the lowest possible emissivity in the rest wavelengths, the use of solar selective absorption coating (SSAC) significantly increased thermal efficiency [7]. A. Dan et al. [8] prepared a novel WAlN/WAlON/Al$_2$O$_3$ SSAC with a high absorptance of 0.958 in the SH band and a low emittance of 0.08 in the infrared region. Furthermore, to examine the augmentation in the heat exchange coefficient between the air and absorber plate, a large number of studies have been conducted in various air duct designs. R. Kumar et al. [9] introduced herringbone corrugated fins to improve the thermal performance the solar air heater. As the numerical results suggest, the thermal efficiency increased from 36.2% to 56.6% with fin pitch 2.5 cm at fixed mass flow rate of 0.026 kg/s. Using experiment, T. Alam et al. [10] investigated the impact of V-shaped perforated blocks on the heat transfer and flow characteristics of the rectangular duct of a solar air heater. Besides, some researchers observed that the artificial surface roughness processed in the air duct or plate effectively increased heat transfer rate. L. Shui-lian et al. [11] presented a novel solar air collector with hemispherical protrusion artificial roughness on the absorber plate. They also studied the performance from two aspects, i.e., optics and thermodynamics. Using experiment, R. K. Ravi et al. [12] studied the impact of roughness parameters on the thermohydraulic performance of the double pass artificial roughened solar air heater duct. The roughness geometry applied on each side of the plate in the double pass mode improves frictional loss and increases heat dissipation rate.

In recent year, radiative cooling (RC), another promising green energy technology, has been broadly studied [13]. RC is a fully passive cooling method exploiting the "atmospheric window"

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(8–13 μm; abbreviated as the "RC band") to dissipate heat from earthbound objects to the cold universe [14]. In line with specific environmental conditions, the RC powers reported in the literature vary from 20 W/m^2 to 130 W/m^2 [15,16]. Dry climate and clear sky contribute to the RC performance. C.Y. Tso et al. [17] verified that a photonic radiative cooler had cooling effect in daytime under California's arid climate but had no daytime cooling effect under humid climate in Hong Kong. Using experiment, M. Hu et al. [18] investigated an integrated solar heating (SH) and radiative cooling collector under various sky conditions. The net RC powers of the collector under clear and overcast skies reached 50.3 and 23.4 W/m^2, respectively. Since the RC power is one magnitude lower than the solar irradiance, a typical RC apparatus primarily operates effectively in nighttime without sunlight. Yet several studies have recently achieved daytime RC with the booming of material science in micro-nano scale. A. P. Raman et al. [19] prepared a photonic coating that can reach a temperature nearly 5 °C lower than that of the ambient air in direct sunlight. Moreover, they created a vacuum chamber with a selective emitter and a ZnSe cover. An average emitter temperature reduction of 37 °C from the ambient air temperature through a 24-h day–night cycle was achieved [20]. From economic perspective, Y. Zhai et al. [21] developed a metamaterial by embedding resonant polar dielectric microspheres randomly in a polymeric matrix, which achieved a noon-time RC power of 93 W/m^2 in direct sunlight.

Heat or cooling energy are critical for building sector of most regions worldwide in different seasons. Furthermore, heat and cooling energy are both required in other fields. For instance, some products need to be dried at high temperature first and then reserved at low temperature in the harvesting process of agricultural products. Though numerous works have increased the thermal efficiency of solar air collectors, these collectors can be applied only for space heating in cold season or for drying agricultural products at harvest time. Likewise, radiative coolers are of significance only in hot seasons or areas. The widespread application of this technology is further hindered by the relatively low RC power density and the accompanying long payback period. However, the noted disadvantages of the two mono-functional collectors can be avoided if solar air heating and radiative air cooling are integrated into a single collector using the same support, collecting plate, frame and cover. The hybrid collector is capable of supplying heat in cold and harvest seasons and producing cooling energy in hot seasons, thus being advantaged in multi-functionality, seasonal adaptability as well as energy saving, compared with solar collectors and radiative coolers. Existing researches have attached the primary importance to a stand-alone SH or RC system. Few studies have focused on comprehensive utilization of SH and RC, in particular based on spectrally selective coatings. M. Matsut et al. [22] first prepared a spectrally selective SH-RC collector and tested its thermal performance preliminarily through a day. The maximum net heating and cooling fluxes yielded in all the experiments reach 610 and 51 W/m^2, respectively. Using a spectrally non-selective coating, Y. Cui et al. [23] proposed a SH and RC wall panel without air gap. As the experimental results suggest, thermal efficiency varies from 27% to 39%, and the cooling power reaches nearly 30 W/m^2. In a previous study, the authors proposed the concept of integrated SH–RC and the ideal spectral characteristics of an SH–RC collecting plate (Fig. 1) [24]. Moreover, a real SH–RC collecting plate was trial-manufactured, and the thermal performance of a water-based SH–RC collector was investigated by performing experiment. The collector showed a thermal efficiency of 62.7% at zero-reduced temperature as well as a net RC power of 50.3 W/m^2 at a clear night [18]. Yet due to the high specific heat capacity of water, the outlet water was hard to fully cool in RC mode. As the specific heat capacity of air is much lower than that of water, it can be cooled to an effective low temperature through the air duct of the collector, which can be directly transmitted to the end user without the need of aftercooling process.

Given that solar air heating and radiative air cooling shows their advantages in simple construction, low-cost and long-life, and superior in practical applications including space heating, crop drying and space cooling, this study proposed an air-based SH–RC collector. This dual functional collector is capable of generating hot air in cold and harvest seasons and supplying cool air in hot seasons. Take space heating and cooling as an example. In daytime and during cold seasons, the cold air in the room is pumped into the air duct of the air-based SH–RC collector and heated by the panel, and subsequently, it flows back into the room; in nighttime and during hot seasons, the indoor warm air is pumped into the air channel, and its heat is dissipated to the panel, and subsequently it flows back into the room as cold air. It is necessary to evaluate the thermal performance of the air-based SH–RC collector through a day by examining it key performance indicators, e.g., daily thermal efficiency at zero-reduced temperature and nocturnal net RC power. Besides, to achieve structural and operation optimizations of the collector, it is of significance to investigating the impact of various parameters (i.e., ambient temperature, inlet air temperature, air flow rate, wind velocity, etc.) on the SH and RC performances of the collector. Moreover, annual thermal performance of the collector is worth studying to be referenced for the use of the collector in various geographic areas and climates. Accordingly, to characterize the thermal performance of the proposed air-based SH–RC collector, this study established a mathematic model falling into two sub-models, i.e., a transitory-state model and a steady-state model. Furthermore, the present work numerically investigated the SH and RC performances of the collector through a summer day and a typical meteorological year, as well as the effect of different parameters on the thermal performance of collector based on the mathematic model.

2. Description of the air-based SH–RC collector

The section structure of the air-based SH–RC collector is shown in Fig. 2. The collector primarily consists of a transparent cover, a collecting plate, an insulation material as well as a frame. The collecting plate has an area of 1964 mm × 964 mm as well as a thickness of nearly 0.4 mm. To enhance the heat exchange coefficient between the plate and air in the air duct, artificially roughed structures were arranged on the lower surface of the collecting plate [26]. The duct is 30 mm in height. Anterior to the collecting plate, a 6 μm thick low density polyethylene (LDPE) film served as the transparent cover to prevent heating or cooling loss by heat convection and to avoid the entry of dust particles and rain [27]. The air gap between the cover and collecting plate was 40 mm. Furthermore, a 60 mm-thick thermal insulation material was provided behind and around the plate. The design was granted a Chinese patent (Patent No. ZL201310494356.0). To the authors' best knowledge, there has been no similar design for the comprehensive use of SH and RC in the market.

The LDPE film shows high transmittance in most 0.2–25 μm spectrum, suggesting that it is a favorable cover to SH and RC. The collecting plate applied in the air-based SH–RC collector is the same as that in the water-based SH–RC collector reported in the previous research, i.e., the TPET collecting plate [18]. This specific plate consists of aluminum plate, Ti-based solar selective absorbing coating as well as polyethylene terephthalate film, as shown in Fig. 2. Through the test of the spectral characteristics of the TPET collecting plate, it is proven that the plate shows clear spectrally selectivity in the 0.2–25 μm region (see Fig. 3). In particular, the plate has a high spectral absorptivity of nearly 0.92 in the SH band,