Energy and Buildings 161 (2018) 72–79

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Performance of a coupled transpired solar collector—phase change material-based thermal energy storage system

Mark R. Poole[a], Sanjay B. Shah[b,*], Michael D. Boyette[b], Larry F. Stikeleather[b], Tommy Cleveland[c]

[a] Civil and Environmental Engineering and Biological and Agricultural Engineering Departments, NC State University, Raleigh, NC 27695, United States
[b] Biological and Agricultural Engineering Dept., NC State University, Raleigh, NC, 27695, United States
[c] Advanced Energy, Raleigh, NC, 27606, United States

ARTICLE INFO

Article history:
Received 14 August 2017
Received in revised form 10 October 2017
Accepted 15 December 2017
Available online 15 December 2017

Keywords:
Ventilation
Tempering
COP
Two-stage
One-stage
UTC

ABSTRACT

The transpired solar collector (TSC) is a low-cost technology for heating ventilation air for mainly for use in industrial and agricultural applications. Storing the excess energy generated during daytime in phase change material (PCM) could improve the economics of using TSCs. Since energy generated for storage could be increased by using a two-stage TSC (with a glazing) vs. a one-stage TSC, first, the thermal performance of the two configurations were compared. Then, performance of the PCM-based thermal energy storage (TES) unit coupled to a TSC was evaluated. At a suction velocity of 0.023 m/s, the one-stage TSC produced a 2 °C higher temperature rise and 8% higher efficiency than the two-stage TSC. The one-stage TSC was coupled to a TES unit packed with 80 kg of salt-hydrate type PCM (specific energy of ∼185 kJ/kg). When evaluated at four airflow rates, the TES unit stored between 76 and 107% of its theoretical heat storage capacity and provided tempered air 4 °C warmer than ambient air during nighttime. While residual energy (for daytime heating) increased with airflow rate, energy charged or discharged was unaffected. Over a week, the TSC-TEC stored 34% of the total useful energy produced for nighttime use, with a potential to displace 1.35 kg of liquefied natural gas. Replacing the expensive metal TSC with a perforated plastic TSC and a simpler TES design would improve the economics of storing solar energy for use after sundown.

1. Introduction

In the US, spacing heating accounts for 42% and 36% of energy use in residential and commercial buildings, respectively [12]201x(a). Use of solar energy for heating can greatly reduce heat energy needs and costs; further, replacing fossil fuel energy with solar energy will reduce or eliminate pollution associated with the production and combustion of these fuels. Solar energy can be used to heat air using several different technologies that vary in price, complexity, and the temperature of air produced. Concentrating collectors (e.g., [29] and vacuum tube solar air collector (e.g., [4] can generate the highest air temperatures but for industrial and agricultural applications, the transpired solar collector (TSC) has good potential [13]201x(b)). The TSC can provide efficiencies reaching 80% and air temperature rises (ΔT) of up to 26 °C [14].

However, despite being less-expensive than other solar thermal systems, the TSC is not used widely because there is less need for preheating of ventilation air during periods (usually, 11 am-2 pm) when high ΔT values are achieved. Storing this excess energy for use later could improve TSC economics and increase usage. Traditionally, solar energy was stored in rock beds or water as sensible heat [18], but these media are bulky and possess low specific energy (MJ/kg). Phase change materials (PCM) that store energy, as latent heat can be formulated for a specific activation temperature and possess higher specific energies. For example, while rocks can store 0.88 kJ/kg-K [27], a salt hydrate based PCM-HS22P can store 185 kJ/kg [26].

There are studies on thermal energy storage (TES) from concentrating, glazed, and vacuum tube solar air heaters (e.g., Arkad and Medved, [4]; Tian and Zhao [29], but the authors could not locate peer-reviewed literature on storage of excess energy generated by the TSC for use after sundown. Shukla et al. [28] proposed using phase change material (PCM) bed in a TSC to absorb energy for use after sundown but there is no evidence that such a system was evaluated. Shah (co-author) mentored student design groups that

* Corresponding author.
E-mail address: sanjay_shah@ncsu.edu (S.B. Shah).

https://doi.org/10.1016/j.enbuild.2017.12.027

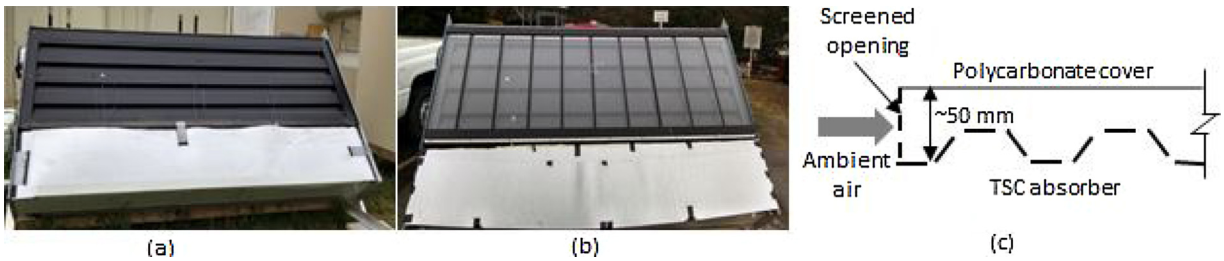

Fig. 1. Transpired solar collector in the (a) one- and (b) two-stage configurations and (c) shows the details of the two-stage configuration. Reflective insulation was placed on the bottom portion to prevent heating from the underlying sheet metal confounding the TSC's performance.

coupled the TSC either with an organic PCM (BioPCM M-51) [9] or with PCM-HSP22P [1] with modest success.

Energy storage increases with thermal gradient between the heat transfer fluid and the storage medium. Compared to a one-stage TSC consisting solely of a perforated collector, a two-stage TSC could provide higher air temperature, allowing for greater energy storage. A two-stage TSC has a glazed (e.g., transparent acrylic) cover over the dark perforated absorber surface. The glazed cover reduces radiative and convective losses, increasing the efficiency of the system but at a higher capital cost. Based on modeling, Conserval Engineering reported that their SolarWall 2-stage TSC gave a 33% higher ΔT than their one-stage TSC (measured ΔT) while the price of the two-stage TSC at \$145/m^2 (excluding freight) was 29% higher (J. Hickey, Personal Communication, 6 July 2017). Zomorrodian and Barati [30] evaluated a bench-scale TSC with a removable glass cover as glazing in one- and two-stage configurations. The one-stage TSC was 25% less efficient than the two-stage TSC ([30]). There is a need additional testing to evaluate a two-stage TSC to see if its increased energy production justifies the extra capital cost.

Hence, the overall objective of this study was to evaluate a combined TSC –thermal energy storage (TES) system. The specific objectives were to (a) compare performances of one- and two-stage TSC configurations and (b) evaluate a PCM-based TES unit coupled to a TSC.

2. Materials and methods

This study was conducted on a corrugated metal TSC that could be operated either as a one-stage or two-stage TSC at North Carolina State University's Poultry Engineering Chamber Complex in Raleigh, NC. The TSC was donated by ATAS International. Additional details are provided in [21].

2.1. Description of the TSCs

The corrugated TSC absorber (Fig. 1) was black anodized aluminum with an absorptance (α) of 0.94 and a porosity of 0.8%; each slit (shaped like a segment of a circle) on the absorber had a hydraulic diameter of ~0.96 mm. The TSC was mounted on a plenum made of metal insulated panels (thermal resistance ≈0.8 m^{2}K/W). While the TSC absorber measured 2.26 m^2, the bottom 1.86 m^2 of the TSC which was black sheet metal, was covered with a radiant insulator (Fig. 1) to prevent confounding of the heating effect of the TSC. The TSC was tilted 50° from the horizontal to maximize irradiance receipt for the test site's latitude as recommended by ATAS. The unit faced south.

The one-stage TSC, described above, was converted into a two-stage unit by covering the absorber with a 0.8 mm thick clear polycarbonate sheet (Fig. 1(b) & (c)). The two-stage TSC was a test unit that had not been commercialized (P. Reinhart, ATAS International, personal communication, 24 April 2017). Conserval Engineering [7] markets a two-stage TSC which differs from the unit evaluated here. Unlike the one-stage unit where the air entered the TSC perpendicular to the absorber, in the two-stage unit, air entered the space between the polycarbonate sheet and the absorber through a screened opening that spanned the width (2.77 m) of the TSC (Fig. 1(c)) and traveled parallel to the absorber until removed by suction. Further, in our unit, the absorber and glazing were parallel to one-another. Conserval Engineering's two-stage TSC as well as the TSC evaluated by Zomorrodian and Barati [30] were more complex, where the glazing and absorber formed an angle with respect to one-another.

Air was pulled through the TSC using a variable speed 0.15-m dia. DC fan (Make: NMB, Model: R150) that provided an airflow rate of 0.053 m^3/s or a suction velocity (V_s) of 0.023 m/s for both stages, where V_s is the ratio of airflow rate to absorber area. Kutscher et al. [19] recommended a minimum V_s of 0.02 m/s to reduce convective and radiative losses in a one-stage TSC. Increasing the V_s would have increased energy produced but it would have decreased ΔT, possibly, preventing the PCM from activating (melting).

2.2. Instrumentation and testing of the TSCs

Inlet (ambient) and outlet temperatures of the TSC were monitored using Maxim DS18B20 temperature sensors (Accuracy: ±0.5 °C), each connected to a wireless transmitter (Manufacturer: Digi International, Model: XB24CZ7UISB003). The outlet temperature was measured upstream of the 250-W fan. The transmitters transmitted the data to Raspberry Pi 2.0 base station (Manufacturer: Raspberry Pi Foundation) every 5 min for storage prior to downloading. A solar radiation sensor (Make: Apogee Model: SP-230, Accuracy: ±5%) mounted adjacent to the absorber used a wireless transmitter to transfer data to the base station every 5 min. Average hourly wind speed (U) data at 6-m height was obtained from the NC CRONOS site located close to the test site.

The one-stage TSC was tested for 34 d (23–29 Mar., 6–30 Apr. 2016) while the two-stage TSC was tested for 7 d (30 Mar. – 5 Apr. 2016); detailed data are presented in [21]. The two configurations were compared for 1 d (for each configuration) when difference in average daily irradiance (I) was <5% and average wind speeds were comparable. The two configurations were compared with respect to temperature rise (ΔT_{tsc} = difference between ambient and outlet temperature, K or °C), power produced (P_o, kw, Eq. (1)), ratio of solar energy input (E_i, MJ, Eq. (2)) to energy output (E_o, MJ, Eq. (3), efficiency ($\eta = E_i/E_o$), and coefficient of performance (COP, Eq. (4)). The equations are given below.

$$P_o = QC_p\rho\Delta T_{tsc} \quad (1)$$

$$E_i = A_{col}I\Delta t \quad (2)$$

$$E_o = P_o t_{op} \quad (3)$$

$$COP = \frac{P_o}{P_{fan}} \quad (4)$$

In the above equations, Q is the volumetric flow rate through the TSC (m^3/s), C_p is the specific heat of air (1.005 kJ/kg-K), ρ is