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Research Paper

Performance study of a dual-function roof solar collector for Chinese traditional buildings application

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HIGHLIGHTS

- A wavelike roof solar collector for Chinese traditional buildings is presented.
- A dynamic model together with experimental validation is conducted.
- Thermal performance of Type 1 collector is compared to the other two collectors.
- Heat loss factor of the Type 1 collector is 54.4% lower than the Type 2 collector.
- Heat loss factor of the Type 1 collector is 65.8% lower than the Type 3 collector.

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ABSTRACT

Architectural integration is a crucial issue in the development and spreading of solar collectors, especially in China, where several traditional buildings have pitch roof with tiles. In this paper, a novel roof solar collector (Type 1) providing hot water and space heating is designed to enable effective collection of solar heat as well integrating naturally. A dynamic numerical model is developed and validated with experimental data. The simulation of the Type 1 collector demonstrates its good characteristics regarding to the thermal insulation and transmission of solar radiation. A linear correlation between the instantaneous efficiency and the reduced temperature is established. Simulated results of the Type 1 collector are further compared with the other two types of roof solar collectors (i.e., Type 2 and Type 3). The comparisons indicated that the similar maximum instantaneous efficiency are achieved. However, the Type 1 collector is preferred as its heat loss coefficient is 54.4% lower compared to the Type 2 collector, and is 65.8% lower compared to the Type 3 collector. The afore-mentioned results confirm that the Type 1 collector introduced has potential to address the issue on the poor architectural quality of roof integrated solar collectors for Chinese traditional buildings.

1. Introduction

The term "solar thermal collector" refers to a heat extracting device that converts absorbing sunlight into thermal energy through a transport medium or flowing fluid, such as air, water or refrigerant. Flat-plate collector, developed by Hottel and Whillier in the 1950s, is the most common type. However, in the early stage the cost effectiveness of this energy system was in doubt as the current up-front costs of solar collector compared to traditional conventional systems, such as boiler heating system, air conditioning system [1]. Subsequently, some researchers proposed integrating solar collect system into the building may decrease the cost of the solar collector systems together with improve the efficiency of the collection. From then on, the researches of the solar collector are continuing today. Mahmut Sami Buker et al. declared that building integrated with solar thermal (BIST) systems can decrease the fuel demand from 50% to 70% for hot water, and 40% to 60% for space heating [2]. Building integrated solar collectors may be installed either on the building wall [3–5] or on the building roof [6,7]. Compared to the BIST wall shaded easily by the surrounding environment, an integrated roof flat plate solar collector (BIST roof) received relatively more attention as the BIST roof can receive the most solar radiation.

The reports on the BIST roofs can be classified into two types of configurations, one with the glazing covered made from tempered glass and the other with the glazing uncovered. Luis Juanico [8] proposed a new concept of roof-integrated water solar collector

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Nomenclature

A	crossection area, m^2
c	specific heat capacity, J/(kg·K)
d	thickness, m
D	external diameter, m
h	heat transfer coefficient, W/(m^2·K)
H	height, m
I	solar radiation, W/m^2
m	mass flow rate, kg/s
N	numbers of copper tubes
Nu	Nusselt number
P	crossection perimeter, m
Ra	Rayleigh number
T	temperature, °C
v	water flow velocity, m/s
w	width, m
Greek symbols	
α	absorptivity
β	thermal expansion coefficient, 1/K
ε	emissivity
ρ	density, kg/m^3
λ	thermal conductivity, W/(m·K)
φ	tilted angle of collector, °
σ	Stefan-Boltzmann constant, W/(m^2·K^4)
Subscripts	
a	ambient
b	back plate
c	glazing cover
w	water
p	absorber plate
t	copper tube
c-a	between glazing cover and ambient
b-a	between back plate and ambient
c-p	between water and absorber plate
b-p	between back plate and absorber plate
w-t	between water and copper tube

that could satisfy the domestic heating and cooling demands. A solar-chimney power plant with an inclined collector roof was simulated by Kim et al. using CFD [9]. Hassan and Belliveau [10] proposed a horizontal roof solar collector replacing the ridge of the roof. Notton et al. [11] designed a new flat transpired solar collector (H2OSS) inserted into a gutter. Hirunlabh et al. [12] studied experimentally the effect of a roof solar collector on the induced natural ventilation. Sultana et al. [13,14] and Petrakis et al. [15] studied the roof integrated mini-parabolic solar collectors and considered that concentrating solar thermal systems offer a promising method to realize rooftop applications for domestic hot water and solar air conditioning. Medved et al. [16] presented the design and the parametric analyses of the efficiency of a large-panel unglazed roof-integrated liquid solar collector. Lin et al. [17,18] and Saman et al. [19] used a corrugated steel roof to function as an unglazed air collector.

The afore-mentioned researches on roof-integrated flat plate solar collectors mostly focused on improving the technical and structural efficiency, and less attention has been paid to the aesthetic quality of the buildings integrated solar thermal collectors. Particularly in China, where several traditional buildings have pitch roofs with tile covers, although a number of BIST roofs have been put into practice currently, the harmony and well combination of the solar collector and pitch roofs cannot be satisfied, as seen in Fig. 1a. To that end, in Refs. [20,21] our group proposed a type of tile-shaped dual-function solar collector (Fig. 1b). The proposed collector can be operated flexibly under water and air heating modes. A new top cover was opportunely mounted on the glass cover of an existing flat dual-function solar collector, which improved the appearance of the buildings integrated solar thermal collectors to some extent as well as reduced the energy loss factor. However, the introduction of top covers in Ref. [20] decreased the solar radiation transmitted to absorber plate and simultaneously increased the up-front cost compared to a traditional roof solar collector. More importantly, the structure will increase the weight of the solar collector, which is undesired when applied on the building roof.

Ideally the glazing should allow maximum solar irradiance to be transmitted and also be able to minimize heat losses from the absorber to ambient. Unlike the system of the collector proposed in Ref. [20], in this paper we propose that using a wavelike top cover directly instead of the tempered glass of a traditional flat-plate collector, which shows better consistency to the tiles on the pitch roof (Fig. 1c). Polymeric methyl methacrylate (PMMA) is selected as the wavelike cover material. The contribution of the PMMA is twofold: Firstly, it exhibits a lower density compared to either the traditional tiles typically made from clay or the tempered glass of solar collector, which is important and beneficial to a building's roof. Secondly, the PMMA is characterized by relatively high transmission of solar radiation and better heat and sound insulation [22]. Therefore, the solution proposed in the present study is very promising from the practical use point of view, especially for Chinese traditional buildings with tiles, which expands the applicable range of the roof- integrated solar collector.

In what follows, we present in the first paragraph the concept of the wavelike roof-integrated solar collector called Type 1 collector and the preliminary experiment implemented in view to test its daily thermal performance. In the second part, a dynamic numerical thermal model of the Type 1 collector is built in MATLAB environment together with the experimental validation. In order to quantify the achievable improvements with the wavelike PMMA cover, the developed model is further used to compare the thermal behavior of the Type 1 with the two collectors in Ref. [20] (Types 2 and 3 collector) under the specified conditions.

2. Description of the roof solar collector and experimental setup

2.1. The dual-function roof solar collector

The structure of the Type 1 collector is shown in Fig. 2. It is composed by a wavelike top cover, followed by an air gap and then a thermal insulated back plate behind. Polymeric Methyl Methacrylate (PMMA) is selected as the wavelike cover material in the developed design and its long-term durability under realistic climate conditions has been proved by the open literatures [22–24], which is characterized by relatively high transmission of solar radiation and better heat and sound insulation. More importantly, the PMMA exhibits a lower density than the most engineering materials (its weight represents only half as much as that of similar thickness made of tempered glass), which is beneficial for the building roof. The gap between the PMMA cover and the back plate is divided by an aluminum absorber plate into up and down channels. There is no air flowing in the up channel to reduce the heat