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Experimental evaluation of an active solar thermoelectric radiant wall system

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ABSTRACT

Active solar thermoelectric radiant wall (ASTRW) system is a new solar wall technology which integrates thermoelectric radiant cooling and photovoltaic (PV) technologies. In ASTRW system, a PV system transfers solar energy directly into electrical energy to power thermoelectric cooling modes. Both the thermoelectric cooling modes and PV system are integrated into one enclosure surface as radiant panel for space cooling and heating. Hence, ASTRW system presents fundamental shift from minimizing building envelope energy losses by optimizing the insulation thickness to a new regime where active solar envelop is designed to eliminate thermal loads and increase the building's solar gains while providing occupant comfort in all seasons. This article presents an experimental study of an ASTRW system with a dimension of 1580 × 810 mm. Experimental results showed that the inner surface temperature of the ASTRW is 3–8 °C lower than the indoor temperature of the test room, which indicated that the ASTRW system has the ability to control thermal flux of building envelope by using solar energy and reduce the air conditioning system requirements. Based on the optimal operating current of TE modules and the analysis based upon PV modeling theories, the number and type of the electrical connections for the TE modules in ASTRW system are discussed in order to get an excellent performance in the operation of the ASTRW system.

1. Introduction

Building envelope plays an important role in building energy consumption [1]. A large amount of energy has needed to compensate for thermal energy losses or gains that occur in building envelope for climate control. This energy consumption comes in the form of use of electrical energy or non-renewable fossil fuels for space cooling or heating. In order to reduce building energy consumption, different passive insulation methods are used to mitigate thermal energy losses or gains in enclosures [2]. Recently, passive solar walls required no electrical or petroleum for operation, which are receiving increasing attention. Passive solar heating is a well-established concept in cold climates. The techniques used for passive heating, such as solar chimney [3], solar room [4], and trombe wall [5,6] are more or less straightforward.

However, both passive insulated walls and solar walls have their own disadvantages: (1) passive insulation cannot effectively control the heat flux and in summer, the insulation perhaps impacted negatively on building energy consumption [7]. (2) Passive solar technology usually can only be used in winter for heating, but in summer, passive solar walls cannot reduce the thermal load of envelope by controlling heat flux. Hence, a novel solar thermoelectric radiant wall (ASTRW) system is proposed in this paper. In ASTRW system, a PV system use solar energy to power a thermoelectric (TE) cooling system and fulfill active control of heat flux in walls. Therefore, the ASTRW system transform the role of the envelope from a passive barrier to heat loss into an active system, thus reducing the need for space heating and cooling and increasing the building's solar gains in all seasons.

Due to the advantages such as high reliability, low weight, and flexibility in packaging and integration, thermoelectric cooler is regarded as clean methods that have been widely used in desalination unit [8], electronic devices cooling [9], and energy recovery products [10]. In addition, due to their bright prospect, some thermoelectric applications are likely to become commercialized, such as domestic-ventilator [11], water heater [12], and thermoelectric cooler system [13,14] which compete with vapor compression based applications. Thermoelectric cooler system can be powered directly by a photovoltaic (PV) without the help of AC/DC inverter. Meanwhile the system is Freon free, causing no harm to the environment. Therefore, the thermoelectric coolers and the solar cells combined technology are beneficial to energy conservation and environment protection [15,16]. Several studies on the solar thermoelectric cooling system have been carried out. Xu and Steven

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Nomenclature

Abbreviates of parameters

COP	coefficient of performance (–)
I	applied current of TE module (A)
Q_c	the total heat flux transferred from the TE modules at the cold junction (W)
Q_h	the total heat flux transferred from the TE modules at the hot junction (W)
Q_l	the heat flux dissipation by insulation materials (W/m^2)
$Q_{c\text{-effective}}$	the effective heat flux for space cooling (W/m^2)
$Q_{h\text{-effective}}$	the effective heat flux for space heating (W/m^2)
T_a	ambient temperature of (°C)
T_c	cold side of temperature of thermoelectric module (°C)
T_h	hot side temperature of thermoelectric module (°C)
T_{in}	temperature of indoor environment (°C)
T_w	the interior surface temperature of traditional wall (°C)
T_r	the mean interior surface temperature of the ASTRW system (°C)
T_1, T_2 and T_3	the interior surface temperature of the ASTRW system (°C)
ΔT	temperature difference of thermoelectric module (°C)
V	applied voltage of TE module (V)
ZT	thermoelectric figure of merit value (–)

tested a solar thermoelectric window system [17]. Sabah et al. designed a solar thermoelectric system, and found that cooing performance was strongly dependent on the hot and cold side temperature of the TE modules [18]. Cheng et al. studied a solar thermoelectric system with a waste heat regeneration system for building application [19]. Liu et al. have studied a solar thermoelectric cooled ceiling combined with displacement ventilation system [20]. In their studies on solar thermoelectric cooling, a number of dates and analyses of great significance have been provided.

The main significance of this paper is to study the active solar wall system integrating thermoelectric radiant cooling and photovoltaic (PV) technologies in the application of solar buildings. Compared with insulated walls and passive solar walls, the ASTRW system converts solar radiation into electrical energy and subsequently uses this electrical energy to power a thermoelectric (TE) cooling system and fulfill active control of heat flux in wall. Capable of operating in both heating and cooling modes, ASTRW systems can be applied for heating as well as cooling applications simply by reversing the direction of direct current in TE component, therefore ASTRW system can be adapted to variable outdoor climate conditions and realize indoor comfort.

2. Experimental setup

2.1. The system working principle

Fig. 1 depicts the prototype ASTRW system currently under development. As shown in Fig. 1, the ASTRW system from the outside to the inside mainly consists of photovoltaic system, airflow channel, and thermoelectric radiant cooling system. The PV forms an envelope surrounding the external wall with an airflow channel maintained between the thermoelectric radiant panel and the PV unit. The TE modules are connected in series and sandwiched between the aluminum radiant panel and the heat sinks. The heat sinks are used to dissipate heat for TE modules. The fan can provide forced air convection to help the TE modules to release heat more efficiently into the airflow channel. In order to reduce energy dissipated into the airflow channel, insulation material was pasted at the back of the radiant aluminum pane. The direction of the heat flow of the wall can be achieved by controlling the direction of the operating current. This feature enables the system useable for different climates.

In cooling mode, the PV system transfers solar energy directly into electrical energy to power the thermoelectric radiant cooling system. The aluminum radiant panel is cooled down by the cold side of the TE modules and thus can realize heat flux controlling. Cold air enters the airflow from the bottom inlet louver, and exchangers heat with the heat sinks that attached to the hot side of the TE modules and the PV system, and then exhaust the waste heat via the outlet louver. In heating mode, the air inlet and air outlet louver are closed and the airflow channel is used to collect heat from the PV, and the current applied on thermoelectric modules is reversed, then the ASTRW system could work as a photovoltaic/thermal (PV/T) system to provide heating capacity for space heating.

A schematic of the heat flows of the ASTRW system based on summer daytime conditions is shown in Fig. 2. The solar energy absorbed by the PV system is partly converted into electrical energy and mostly is dissipated as waster heat through the airflow channel into environment. The electrical energy is subsequently used to power the thermoelectric (TE) radiant cooling system. The heat of the hot side of the TE modules is dissipated by the heat sink into environment.

It can seen form Fig. 2, the heat flux produced by the TE modules is the total heat flux of the ASTRW system. Most of the heat flux is transferred by the aluminum panel for space cooling, and still a little is dissipated through the thermal insulation material that pasted at the back of the radiant aluminum panel.

2.2. Experiment setup

As can be seen in Fig. 3, the experiment was carried out in an experimental room. The experimental room with an open area around is 3 m × 3 m × 3 m in dimension. The ASTRW system is constructed in the south of the experimental room. As shown in Fig. 3, the dimension of the PV and the aluminum panel are both 1580 × 810 mm, and the air inlets above and below the PV are both 1580 × 100 mm. A split air conditioner and an electrical heater are used to control the temperature of the test room, which permits room air temperature to be fixed to an approximately constant value in tests.

Ten TE modules are used in the ASTRW system, all of them are uniformly distributed in the aluminum panel, and two times five TE modules were connected in series, with both series connected to the PV power sully in a parallel circuit as shown in Fig. 3. The thickness of the insulation material is 40 mm, and the thermal conductivity of the insulation materials is 0.002 W/m k. The heat pipe sinks for TE modules heat dissipation are commercial heat pipe, called yinhua, and a 1.2 W fan for each heat pipe sink was used to cool down the heat pipe. The fans powered by a DC power. The rated power output for the PV panels is about 170 W (25V DC), and other parameters include a short-circuit current (i_{PV}-ss = 5.05 A), open-circuit voltage (υ_{PV}-oc = 44.2 V), and maximum power ($\upsilon_{PV\text{-max}}$ = 35.8 V, $i_{PV\text{-max}}$ = 4.75 A). These values are based on the assumption that it is normal to expose the panel's surface under 1000 W/m^2 of solar radiation. The TE modules were purchased from FERROTEC Corporation and the size of the TE