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Experimental study and performance analysis of a thermoelectric cooling and heating system driven by a photovoltaic/thermal system in summer and winter operation modes

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ABSTRACT

This paper presents theoretical and experimental investigations of the winter operation mode of a thermoelectric cooling and heating system driven by a heat pipe photovoltaic/thermal (PV/T) panel. And the energy and exergy analysis of this system in summer and winter operation modes are also done. The winter operation mode of this system is tested in an experimental room which temperature is controlled at 18 °C. The results indicate the average coefficient of performance (COP) of thermoelectric module of this system can be about 1.7, the electrical efficiency of the PV/T panel can reach 16.7%, and the thermal efficiency of this system can reach 23.5%. The energy and exergy analysis show the energetic efficiency of the system in summer operation mode is higher than that of it in winter operation mode, but the exergetic efficiency in summer operation mode is lower than that in winter operation mode, on the contrary.

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1. Introduction

In the past decades, because of the development of the economic and industrial, the non-renewable and polluting fossil fuels were consumed largely. And it is necessary to explore new energy to remit the needing pressure of energy. The solar energy is a new way to relieve the pressure, because it is pollution free and easy to gain. Many devices have been designed to gain solar energy. Flat-plate solar collector is steady and efficient and it has been widely used in residential water, space heating and commercial or industrial applications. Its efficiency can be improved by reducing its size and obtaining higher temperature fluid at outlet. There are many different highly-effective techniques which have been used in the past to enhance the thermal performance of solar collectors including the methods of reducing the heat loss from the top surface [1,2] or increasing the energy gain inside the solar converter [3,4]. The building-integrated dual-function solar collector is a new structure collector which can perform in two different modes: working as a passive space heating collector in cold sunny days such as in winter or working as a facade water heating collector in hot days such as in summer [5–7].

The PV/T system has been researched widely because it can use solar energy more sufficiently to produce electrical and thermal energy simultaneously. Henning Helmers and Korbinian Kramer presented a performance model that enables yield predictions of hybrid photovoltaic and thermal (PVT) collectors. It applied for both non-concentrating (PVT) and concentrating (CPVT) systems. The model was based on considerations of energy balance, heat transfer and the dependence of the photovoltaic efficiency on absorber temperature and applied to measurement data of a CPVT collector to exemplify the procedure and to validate the model [8]. Faizal reported the energy, economic and environmental analysis of metal oxides nanofluid for flat-plate solar collector which used nanofluid as working fluid. From the study, it was estimated that a large number of solar collectors can be saved for CuO, SiO_2, TiO_2 and Al_2O_3 nanofluid. The average value of 220 MJ embodied energy can be saved for each collector, 2.4 years payback period can be achieved and around 170 kg less CO_2 emissions in average can be offset for the nanofluid based solar collector compared to a conventional solar collector [9]. da Silva and Fernandes researched the thermodynamic modeling of hybrid photovoltaic–thermal (PV/T) solar systems, pursuing a modular strategy approach provided by Simulink/Matlab. And the results showed that the modular approach strategy provided by Matlab/Simulink was applicable to solar systems modeling, providing better code scalability, faster developing time, and simpler integration with

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Nomenclature

A	contact area, m^2
C_p	heat capacit, J/(kg K)
$\dot{E}_{pv}$	photovoltaic output power per unit cell area, W/m^2
$\dot{E}_{te}$	thermal output power per unit collector area, W/m^2
$\dot{E}\chi_{pv}$	photovoltaic exergy output per unit PV cell area, W/m^2
$\dot{E}\chi_{te}$	thermal exergy output per unit collector area, W/m^2
$\dot{E}\chi_{sun}$	exergy input of solar radiation, W/m^2
G_T	solar irradiance, W/m^2
I	current, A
K	thermal conductivity, W/(kg K)
L	thickness, m
M	quality, kg
P	power, W
Q	Heat flux, W
R	thermal resistance, K/W
R'	thermal contact resistance, K/W
R''	contact resistance coefficient, m^2 K/W
S	area, m^2
T	temperature, K
ΔT	temperature variation of water, °C
U	voltage, V
α	absorptivity or Seebeck coefficient thermoelectric materials, V/K
β	Boltzmann's constant, W/(m^2 K^4)
ε	Exergetic efficiency
η_{te}	thermal efficiency of the system
η_{pv}	electrical efficiency of solar cells
η_{pvt}	total efficiency of the system
κ_{panel}	emissivity of absorber panel
σ	conductivity of the thermoelectric materials, s/m
τ	Interval time of data collection, s
ξ	PV cell packing, factor

Subscripts

1	ceramic shell of thermoelectric device
2	radiator
3	foam wall
4	brick wall
5	copper plate
6	water block
a	ambient environment
c	cold side of thermoelectric module
h	hot side of thermoelectric module
heat-hr	hot side of thermoelectric module and experimental room
heat-cw	cold side of thermoelectric module and heating water
n	number
pipe-t	top of heat pipe
pipe-m	middle of heat pipe
pipe-b	bottom of heat pipe
panel	absorber panel
r	experimental room
s	thermoelectric module
solar	PV cell
t	thermoelement
te	thermal energy
w	water in the storage tank

external computational tools, when compared with traditional imperative-oriented programming languages [10]. Highly thermal efficiency can be achieved via the combination of solar collector and other devices. The composite structure of solar collector and heat pump is common one. José Fernández-Seara and Carolina Piñeiro reported the experimental analysis of a direct expansion solar assisted heat pump with integral storage tank for domestic water heating under zero solar radiation conditions [11]. Moreno-Rodríguez and González-Gil presented the theoretical model and experimental validation of a direct-expansion solar assisted heat pump for domestic hot water (DHW) applications. The acquired experimental coefficient of performance was found to be in the rank of 1.7–2.9.The DHW tank temperature over the course of the study is 51 °C[12]. S.K. Chaturvedi researched the solar-assisted heat pump which was sustainable for low-temperature water heating applications. Results indicated that the DX-SAHP (Direct expansion solar assisted heat pump) water heaters systems when compared to the conventional electrical water heaters were both economical as well as energy conserving. The analysis also revealed that the minimum value of the system life cycle cost was achieved at optimal values of the solar collector area as well as the compressor displacement capacity [13]. Gang and Huide presented a dynamic model of a heat pipe PV/T system and constructed a test rig. Experiments were conducted to validate the results of the simulation. Based on the validated module, the performances of the heat pipe PV/T system were studied under different parametric conditions, such as water flow rates, PV cell covering factor of the collector, tube space of heat pipes, and kinds of solar absorptive coatings of the absorber plate [14].

Solar thermoelectric refrigerator were reported by many researchers [15–17], but thermoelectric heating was not a common research field. This article introduced the application of combining of PV/T system, thermoelectric modules and building. The summer operation mode of the system which can provide cooling for room and heat domestic hot water for user was tested with the small-scale version [18]. The results indicate the system has a higher electrical efficiency (15.4%) and thermal efficiency (29.4%), and the thermoelectric module has a strong cooling ability that COP is about 0.45. Now the experimental performance and theoretical analysis of the system in winter operation mode are presented in this paper. And energy and exergy analysis are also done in summer and winter operation modes, which are validated by the small-scale system and this paper.

2. Experimental structure and working principles of the system

2.1. Experimental structure

The experimental structure of the thermoelectric heating system driven by a heat pipe PV/T panel is shown in Figs. 1 and 2.

The system is composed of a heat pipe PV/T panel, model of maximum power point tracking and controling the solar charge, experimental room, thermoelectric modules, heat exchangers, pumps, fans and storage tank. The experiment was carried out on the sunny days of winter. The dates which were recorded include the temperature of the PV/T panel, heat pipe, the cold side and hot side of thermoelectric modules, the experimental room and comparative room, ambient and the water of storage tank, the solar irradiance, the output Voltage and current of the PV/T system, the input Voltages and currents of thermoelectric modules, the amount electricity used in the experimental and comparative room in which EHS used. The difference of the mathematical models between the summer operation mode and winter operation mode is that the direction of current input is opposite, hence the hot side

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