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Operational performance study on a photovoltaic loop heat pipe/solar assisted heat pump water heating system

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ABSTRACT

A new photovoltaic loop heat pipe/solar assisted heat pump (PV-LHP/SAHP) water heating system was introduced in this paper. With the combination of solar energy, LHP and heat pump technology, the composite system could operate in the PV-LHP mode, the solar/air source heat pump (SASHP) mode and the air source heat pump (ASHP) mode. The mathematical model of the system was constructed to simulate operating performances in typical working conditions and in long-term run. The influence of main structure and operating parameters were also analyzed. To validate the accuracy of the built model, an outdoor test rig of the PV-LHP mode was established in Qinhuangdao City. Investigation results showed that the overall photothermal efficiency of the system is comparable to traditional photovoltaic/thermal (PV/T) water heating systems. The monthly average power consumption per liter hot water is 0.009 kW h/L, and the monthly average COP of heat pump modes is about 3.10. Besides, the annual solar heating ratio of the system is up to 57.8%. Compared with the traditional ASHP system, the life cycle cost of the PV-LHP/SAHP system could be reduced by 29.6%.

1. Introduction

Electricity needs and hot water demands are considerable in the building sector. To reduce fossil fuels energy consumption, photovoltaic solar assisted heat pump (PV-SAHP) systems, which combine solar PVT collectors with heat pump technology, have been proposed and studied by several researchers [1–4]. Their investigation results indicate the thermal performance of PV-SAHP systems is better than traditional heat pump systems and the photovoltaic efficiency is also improved. However, continuous electricity consumption is necessary during the operation of the PV-SAHP systems.

The loop heat pipe (LHP) has been widely utilized in thermal control of satellites, spacecrafts, electronics and cooling/heating systems [5,6]. Use of LHP for solar energy collection and transportation is the only recent development and still at the research stage [7]. Pei et al. [8,9] designed a novel heat pipe-type PV/T to solve the freezing problem associated with the traditional PV/T system. Outdoor tests were carried out, the performances of the system with and without glass cover were also studied. Zhang et al. [10] combined LHP with SAHP. They found that the utilization ratio of solar energy is raised and more energy saving is realized. Fu et al. [11] further proposed a photovoltaic solar-assisted heat-pump/heat-pipe (PV-LHP/SAHP) system, which connects an air-cooled heat exchanger parallel to the heat-pipe PV/T collectors as an auxiliary evaporator of the heat pump. A series of experiments were conducted in Hong Kong to study the performance of the system when operating in the heat-pipe and the solar-assisted heat-pump modes. Huang et al. [12] presented a heat-pipe enhanced solar-assisted heat pump water heater (HPSAHP), which operates in heat-pump mode when solar irradiation is low and in heat-pipe mode without electricity consumption when solar irradiation is high. He et al. [7,13] investigated the operational performance of a novel heat pump assisted solar façade LHP water heating system using both theoretical and experimental methods. The results indicate that the thermal efficiency of the LHP module was increased by 22.2%, with the integration of the heat pump. There have been other related studies [14–17] to integrate LHP with solar PV/T technology for hot water supply or space heating. To the authors' knowledge, the most previous literature mainly focused on the novel structures of the heat pipe PV/T system or analyzed the operating performance of combined LHP/SAHP systems in subtropical climatic conditions. There were limited studies about the combination of LHP with a multi-source heat pump unit and its feasibility in cold areas.

In the present study, therefore, a photovoltaic LHP solar-assisted heat-pump (PV-LHP/SAHP) system, which is an integration of PV/T collectors, LHP and a SAHP, is proposed for hot water production in residential buildings. Based on cold climatic weather conditions, operating performance of the PV-LHP/SAHP system in typical

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Nomenclature

I	Solar irradiation (W/m^2)
c	Specific heat capacity (J/(kg K))
l	Thickness (m)
T	Temperature (K)
Q_{cg}	Solar irradiation absorbed by glass cover (W/m^2)
Q_e	Photoelectric power of PV cells (W/m^2)
Q_p	Solar irradiation absorbed by PV modules (W/m^2)
h	Heat transfer coefficient (W/(m^2 K))
u_w	Outdoor wind speed (m/s)
Nu	Nusselt number of air convection between glass cover and PV layer
R	Heat transfer resistance ((m^2 K)/W)
A	Area (m^2)
M	Mass (kg)
D	Diameter (m)
N	Number
k	Thermal conductivity coefficient (W/(m^2 K))
B_r	Temperature coefficient of PV cells
T_r	Standard test temperature of PV cells (K)
A_c	Area of PV/T collector (m^2)
A_{bi}	Surface heat transfer area of single absorption-pipe (m^2)

Greek

θ	Solar incidence angle (°)
β	Installation angle of PV/T collector (°)
ρ	Density (kg/m^3)
ε	Infrared emissivity
σ	Stephen-Boltzmann constant
ζ	Coverage factor of PV cells
λ	Thermal conductivity (W/(m K))
τ	Penetration ratio
η	Efficiency
η_r	Photovoltaic conversion efficiency of PV cells at standard test temperature

Subscripts

bt	Beam total
dt	Diffuse total
w	Water
cg	Glass cover
a	Air
p	PV
r	Irradiation
r, p-cg	Irradiation, between PV panel and glass cover
c, p-cg	Convection, between PV panel and glass cover
TPT	Tedlar PET Tedlar
p, c	Condenser pipe
p, e	Evaporator pipe
c, a	Between absorption panel and surroundings
c, b	Between absorption panel and evaporator pipe
c	Thermal absorption layer
e, c	Evaporator and condenser
e, p	Evaporator pipe wall
c, p	Condenser pipe wall
a, pv	Between absorption panel and PV modules
e, wick	Evaporator wick
c, i	Condensation, in condenser pipe
e, o	Evaporator pipe, outside
e, i	Evaporator pipe, inside
ap	Absorption-pipe
wick, o	Wick, outside
wick, i	Wick, inside
c, w	Between condenser pipe and water
w, in	Water, inlet

working days and in long-term run was simulated. And influences of main structure and operating parameters were also analyzed.

2. System description and operating principles

Fig. 1(a) illustrates the schematic diagram of the target PV-LHP/SAHP system, which combines the PV-LHP with the solar assisted air source heat pump loop. The PV-LHP loop, as shown in Fig. 1(b), is mainly composed of a flat-plate PV/T collector with single glass cover, a vertical coil condenser incorporated into a water tank, the evaporator/condenser connection pipes, an electric control and storage unit (controller, inverter and battery) and valves. And the condenser water tank is installed higher than the PV/T collector/evaporator by about 0.6 m to accomplish the circulation of working medium (i.e. R22). During the daytime, i.e. from 8:00 to 15:00, valve 1 and valve 2 would be opened while valve 3 and valve 4 would be closed, and the system would operate in the PV-LHP mode when solar radiation is higher than 300 W/m^2. When solar radiation is sufficient, the PV/T collector collects solar energy and heats absorption pipes, and the working fluid evaporates and absorbs the solar heat. Driven by buoyancy, R22 stream floated upwards and entered the condenser in the water tank. In the condenser, the working fluid condenses and releases its latent heat into the water. After that, the condensed working fluid flows back to absorption pipes by gravity and one working cycle of the PV-LHP mode is finished.

As for the solar assisted air source heat pump loop, it is consisted of a flat-plate evaporator with straight fin and no glass cover, a condenser shared with the LHP loop, a rotary compressor, the capillary and valves. After the operation of the PV-LHP, i.e. after 15:00, valve 3 and valve 4 would be opened while valve 1 and valve 2 would be closed. In this case, the system would run in solar/air source heat pump (SASHP) mode when solar radiation is above 0 W/m^2. When no solar energy was obtained in cloudy and rainy days, the evaporator of the heat pump loop absorbs energy only from ambient air and the system would run in the air source heat pump (ASHP) mode. The same working fluid R22 is adopted in three operation modes. Design specifications of the PV-LHP/SAHP system are shown in Table 1.

Table 1
Design parameters of main device.

Device	Parameters
PV/T collector	Glass cover: 3.2 mm, α_{cg} = 0.91 Absorption panel: Aluminum, 1.87 m^2 Absorption pipe: red copper φ10 × 0.5 mm PV panel: monocrystalline silicon 125 mm × 125 mm-64
Evaporator	Absorption panel: aluminum, 0.4 mm, 2 × 1.5 m^2 Absorption pipe: red copper φ10 × 0.5 mm Fin: space (5 mm), height (11 mm)
Condenser	Condensing pipe: red copper φ12 × 1 mm Coil diameter: 30 mm Water tank: stainless steel, 150 L
Compressor	Displacement: 21.1 cm^3/rev Speed: 3600 r/min