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Experimental investigation of a solar collector integrated with a pulsating heat pipe and a compound parabolic concentrator

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ABSTRACT

The paper reports an experimental investigation of a newly proposed solar collector that integrates a closed-end pulsating heat pipe (PHP) and a compound parabolic concentrator (CPC). The PHP is used as an absorber due to its simple structure and high heat transfer capacity. The CPC has a concentration ratio of 3.4 and can be readily manufactured by three-dimensional printing. The CPC can significantly increase the incident solar irradiation intensity to the PHP absorber and also reduce the heat loss due to the decrease in the area of the hot surface. A prototype of the solar collector has been built, consisting of a PHP absorber bent by 4 mm diameter copper tube, CPC arrayed by 10 × 2 CPC units with the collection area of 300 × 427.6 mm^2, a hot water tank and a glass cover. HFE7100 was utilized as the working fluid at a filling ratio of 40%. The operating characteristics and thermal efficiency of the solar collector were experimentally studied. The steady and periodic temperature fluctuations of the evaporation and condensation sections of the PHP absorber indicate that the absorber works well with a thermal resistance of about 0.26 °C/W. It is also found that, as the main factor to the the thermal performance of the collector, thermal resistance of the PHP absorber decreases with increasing evaporation temperature. The collector apparently shows start-up, operational and shutdown stages at the starting and ending temperatures of 75 °C. When the direct normal irradiance is 800 W/m^2, the instantaneous thermal efficiency of the solar collector can reach up to 50%.

1. Introduction

Solar energy is one among the most abundant, inexpensive, environment-friendly energy that can potentially meet the world's growing energy demand. The efficient mean to utilize solar energy is to convert solar energy into heat stored in water by solar thermal collectors [1]. Evacuated tube collectors and flat-plate solar collectors are the most commonly and widely used stationary solar collectors [2]. High-efficiency heat transfer absorber and solar radiation concentration are the main methods to improve the performance of the solar thermal collector. Pandey and Chaurasiya [3] presented an overview on the different techniques to enhance the efficiency of flat plate collectors. The application of nanofluids as heat transfer fluid can improve the thermal efficiency of the collectors. Verma et al. [4] experimentally investigated the effect of a wide variety of nanofluids on the performance of flat plate solar collector. The thermal efficiency was improved by 23.5% using multiwalled carbon nanotubes/water instead of water up to 72.5%. In vacuum tube collectors, the efficiency was improved by 71.8% up to 93.4% due to the improved thermal properties of single walled carbon nanotubes nanofluid [5]. The combination of heat pipe and evacuated tube is an efficient way of solar collector due to its high heat transfer capacity. However, the thermal resistance between the absorber face of the vacuumed tube and the heat pipe determined the efficiency of the collector. The desalination efficiency was improved from 21.7% to 65.2% by using oil as the added fluid to the space between heat pipe and evacuated tube collector in a new desalination system using a combination of heat pipe and parabolic through collector [6].

Pulsating heat pipe (PHP), which was proposed by Akachi [7] in the early 1990s as a new member of heat pipe, is one of the highly efficient absorber with simple structure and low-cost. At a steady state working stage, a self-sustained thermal-driven oscillating flow inside the tube is achieved leading to higher heat transfer rate. Different from a traditional heat pipe, the sensible heat of the working fluid plays a major role in heat transfer [8]. Furthermore, complicated two-phase heat transfer occurs at a capillary scale.

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Nomenclature

A	area (m^2)
CR	concentration ratio of CPC
c	specific heat capacity (kJ/kg K)
d	diameter (m)
D	aperture width (m)
H	height of CPC (mm)
m	mass flow rate (kg/s)
n	number of PHP turns
I	solar irradiation density (W/m^2)
ID	inner diameter (mm)
i	the number of a thermal couple
OD	outer diameter (mm)
Q	heat (W)
q	heat flux (W/m^2)
T	temperature (°C)
R	thermal resistance (°C/W)

Greek symbols

η	efficiency of the solar collector
σ	surface tension of the working fluids (N/m)
ρ	density of the working fluids (kg/m^3)
φ	angle between the incident ray and the X-axis (°)
θ_A	aperture angle of the CPC (°)

Subscripts

1–14	location of thermal couples
c	condensation section
e	evaporation section
in	inlet of the hot water tank
l	liquid
r/rad	radial direction
out	outlet of the hot water tank
p	plate
s	solar energy
T	temperature
w	water
v	vapor

Previous efforts have mainly been focused on explaining the working principle of PHPs. Heat flux has a significant effect on the thermal performance of PHP [9]. There are three working states of PHP, start-up, steady state and dry-out as the heat input increases. There exists a threshold heat flux at which PHPs start to operate. The thermal resistance of the PHPs decreases as the heat flux increases at steady state [10]. The operational regimes, including the start-up and dry-out under different heat inputs, were discussed in detail [11]. Kim and Lee [12] experimentally investigated the effect of channel geometry on the operating limit of microchannel pulsating heat pipes. The results showed that the square microchannel PHP can offer approximately 70% higher maximum allowable heat flux than the circular microchannel PHP at the same hydraulic diameter. Asymmetric channels decreased the thermal resistance of PHP under certain heat inputs [13].

Over the last decades, an increasing amount of attention has been paid to the applications of PHPs, especially in the field of space, electronic cooling, heat recovery and solar thermal applications. A PHP air-preheater was designed and tested in a dryer and played a role of energy recovery and dehumidification [14]. PHP was also applied in a wire-on-tube heat exchanger as an extended surface and the heat transfer rate of the heat exchanger increased under different conditions [15,16]. An unlooped PHP has been developed and tested in an electronic thermal management field with hybrid vehicle applications and the PHP functioned with high reliability and reproducibility and without any failure during the start-up or working stage [17]. A simplified theoretical model of PHP employed as the condenser in a vapor compression refrigeration system has been built. The performance of the system was improved [18]. PHP had also been used as heat sink of a high power LED street light [19] and defrosting plate [20].

In the field of solar energy collection, the use of PHP as the heat receiver has presented an efficient performance that is comparable to that of the traditional heat pipe receiver. PHPs possess the advantages of simple structure, low cost, and high efficiency. Rittidech and Wannapakne [21] built a PHP flat-plate solar collector in 2007. The collector was placed on a sheet of black zinc and had a collection area of 2.00×0.97 m^2. An efficiency of approximately 62% was achieved. Choi et al. [22] investigated the effect of the working fluid filling ratio and the cooling water flow rate on the top heat loss and performance of a PHP flat-plate solar collector. The radiation intensity was realized by using a halogen lamp solar simulator. The effect of evaporator length on the efficiency of a PHP flat-plate solar collector has also been investigated [23] and a multilayer perceptron neural network was trained and used to predict the behavior of the solar collector [24]. The maximum predicted thermal efficiency of the collector is 61.4%. An extra-long PHP was designed, constructed, and installed in a thermosiphon solar water heater, and the operating characteristic was investigated. Several sets of PHPs were placed in glass tubes to create a solar collector, another form of PHP receiver [25,26]. An efficiency of approximately 76% was achieved [25], and the heat loss was reduced by the addition of the glass tube.

The PHP exhibits a great potential for use as a heat collector because of its high heat transfer capacity. However, the heat flux of the evaporation section of PHP should be sufficiently high to meet the demand of its steady and high-efficiency work, which has a significant effect on the thermal performance of PHP [9]. Several experimental studies of PHP with similar structure to the PHP collector are listed and compared in Table 1. We can find in the application of PHP as solar heat collector or absorber the heat flux of the evaporation section is much lower than those in the experimental studied, which can be increased to improve the thermal performance of PHP. To this end, a solar concentrator is necessary. Compound parabolic concentrator (CPC), which is frequently utilized in low-temperature applications as a concentrating non-imaging concentrator [27], is introduced to concentrate solar radiation to the PHP absorber. Therefor, a novel solar collector integrated with a PHP and a CPC is proposed. The introduction of CPC with a proper concentration ratio can increase the heat flux of the PHP absorber so that the efficient heat transfer capacity of PHP is fully utilized. In the new collector, solar energy is concentrated by CPC instead of the plate-absorber of the plate solar collector. The heat loss of the new collector will be reduced by decreasing the hot surface area. From another point of view, the disadvantage of CPC is the size, which depends on the size of the absorber, affecting the combination of the CPC collector and buildings. The diameter of PHP is usually not more than 4 mm that is much smaller than the traditional heat pipe absorber. When PHP is used as absorber, the size of CPC can be same as that of the plate solar collector. This makes it easy to combine the new collector to buildings.