Applied Energy 206 (2017) 708–722

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A numerical and experimental study of micro-channel heat pipe solar photovoltaics thermal system

Mawufemo Modjinou, Jie Ji*, Jing Li, Weiqi Yuan, Fan Zhou

Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei 230026, China

HIGHLIGHTS

- A novel photovoltaic/thermal system with micro-channel heat pipe was proposed.
- A detailed simulation model for the MHP-PV/T system was presented.
- Heat transfer limitations and transient study of the components have been analyzed.
- The hydrodynamic and vapor transient periods of the refrigerant was identified.
- The thermal and electrical efficiency of the MHP-PV/T has been calculated.

ARTICLE INFO

Keywords:
Micro-channel heat pipe
c-Si
Solar
Photovoltaic
Thermal

ABSTRACT

A novel micro-channel heat pipe array incorporated with crystalline silicon (c-Si) solar photovoltaic/thermal system (MHP-PV/T) was designed and constructed by the authors. The proposed design configuration combined c-Si solar cells and wide micro-channel heat pipes (MHP) that were filled with prescribed amount of acetone as refrigerant under a vacuum condition in the same insulated frame to simultaneously provide electrical and thermal energy. Heat and mass transfer characteristics of the MHP-PV/T were preliminary investigated using both numerical and experimental methods. The transient behavior and parametric heat transfer limitations of the heat pipe were also examined using MATLAB. A linear relation between the thermal instantaneous efficiency η_{th} and the reduced temperature parameter $(T_{out}-T_{in})G_T^{-1}$ was established. The maximum instantaneous efficiency was found to be 54.0% with an electrical power output of 70 W. The results indicated that the daily thermal and electrical efficiencies were 50.7% and 7.6%, respectively. The transient behavior of the MHP shows a faster thermal response to heat input within the temperature range of 48.8–49.2 °C and slower response when the thermal diffusivity was reduced to 0.05 cm^2/s. The results also reveal good agreements between model simulation and experimental measurement with sufficient confidence.

1. Introduction

In order to utilize the solar photovoltaic (PV) cell at a low operating temperature, researchers focus on cooling the solar cell and taking advantage of the heat dissipated from the solar cell using fluid channels at the rear of the solar cell or heat pipe. The technology incorporates a solar PV module and a solar thermal collector in the same frame to convert solar energy into electrical and thermal energy simultaneously. This kind of solar system is termed photovoltaic/thermal (PV/T) system. The system can provide hot water while producing electricity at the same time. These dual functions of the PV/T result in a higher overall solar energy conversion rate than the sole use of photovoltaic modules or solar water heaters [1]. The first investigation on a PV/T system was presented by Wolf [2]. Subsequently, several kinds of research on the hybrid solar PV/T system have been carried out to improve its general performance [3].

Since an improvement on PV/T technology makes it cost-effective, a considerable amount of research has been carried out to investigate the performance of PV/T system over the years [4]. However, these studies were done using conventional or standard heat pipes also known as constant conductance heat pipes (CCHPs) [5]. Although researchers recognize the effectiveness of micro-channel heat pipes (MHP) over conventional heat pipes, there were hardly any studies designed to examine the performance of MHP incorporated with PV/T [6]. MHP has noticeable leads over standard round tubes heat pipes (RTHP) and unlike other conventional heat pipes; MHP is precisely flat with width

* Corresponding author.
E-mail addresses: mawufemo.m@gmail.com (M. Modjinou), jijie@ustc.edu.cn (J. Ji).

http://dx.doi.org/10.1016/j.apenergy.2017.08.221
Received 29 May 2017; Received in revised form 7 August 2017; Accepted 27 August 2017
Available online 08 September 2017
0306-2619/

Nomenclature

Symbols

A	cross-sectional area [m^2]
C	specific heat [J/(kg K)]
E	output electricity [W/m^2]
F_R	heat removal factor of the MHP-PV/T [dimensionless]
G	solar irradiance [W/m^2]
g	acceleration due to gravity [m/s^2]
H	air gap [m]
h	heat transfer coefficient [$W/(K{\cdot}m^2)$]
I	current of photovoltaic module [A]
L	latent heat [J/kg]
m	mass [kg]
$\dot{m}$	mass flow rate [kg/s]
M	measured data
n	derivative in the normal direction at the interval boundary
R	thermal resistance [K/W]
T	temperature [K or °C]
fh	fluid film height
M	mass per unit area [kg/m^2]
Nu	Nusselt number [dimensionless]
Q	heat [W/m^2]
P	predicted data
q	heat flux [W/m^2] or the rate of internal heat supplied [W/m^3]
qe	evaporator net heat flux [W/m^2]
Ra	Rayleigh number [dimensionless]
U	conduction heat transfer coefficient per unit length [W/(m K)]
u	average wind speed [m/s]
V	voltage of photovoltaic module [V]
y	horizontal coordinate [m] or [cm]
z	axial coordinate [m] or [cm]

Subscript

a	air
amb	ambient
b	back or photovoltaic cells back metal contact materials
c	collector
$cond$	condenser
e	external environment
es	heat pipe external surface
eff	effective (thermal conductivity)
$evap$	evaporator
f	energy saving
$final$	final
g	glass cover
in	inlet or input
pv	photovoltaic cells
MHP	micro-channel heat pipe
ref	reference
L	loss coefficient of the MHP-PV/T
$loss$	loss coefficient of the system
l	refrigerant film
l	liquid refrigerant
out	outlet or output
sky	sky
sat	saturated
th	thermal
$trans$	transverse
T	total
v	vapor
w	wall of the heat pipe

Greek symbols

α	thermal diffusivity [m^2/s]
δ	thickness [m]
ε	emissivity [dimensionless]
λ	thermal conductivity [W/mK]
σ	Stefan-Boltzmann constant [5.6697×10^{-8} $W/(m^2 K^4)$]
Ø	MHP-PV/T collector tilt angle [rad]
ζ	packing factor
τ	transmittance [dimensionless]
$(\tau\alpha)_e$	effective transmittance-absorptance product [dimensionless]
υ	kinematic viscosity [m^2/s]
γ	thermal expansion coefficient [K^{-1}]
$(\Delta\eta)$	overall uncertainty

ranging from 1.2 mm to 4.0 mm. It has better heat transfer capacity, lower pressure difference, lower filling ratio and more compact structure [7]. It has the advantage of eliminating a cost and product thickness compared to RTHP. It is used in electronic systems to remove a large amount of heat and was only reported by limited studies in solar thermal energy conversion area [8].

In spite of the advantages of MHP, only a few studies investigated its performance with collectors [9]. Deng et al. studied the thermal performance of a system of MHP thermal collector and indicated that the system of heat pipe has an excellent performance, including quick thermal respond speed and agreeable isothermal ability [10]. Past innovative studies only focus on other components of the PV/T systems to improve its performance. For instance, Wang and Pei [11] investigated the effects of frame shadow on PV/T system and showed that the frame shadow reduced the efficiency to 3.2% with a total annual energy loss of 53.6 kWh/m^2. Huang et al. [12] and Kalogirou et al. [13] also studied the overall energy gain of PV/T to find potentials of improving its performance. Many designs of PV/T systems have been introduced without paying much attention to the heat transfer mechanism. Mat et al. indicated by a review study that the tube-and-sheet and evacuated tubular PV/T systems that were presented in literature made use of RTHP. The heat pipes used were of circular cross section [14]; and experimental studies by Riffat et al. [15] and Hammad [16–19] likewise.

Even though MHP has noticeable leads over RTHP, there were hardly any studies designed to examine its performance with PV/T systems. Ji Jie and his team are presenting this paper to fill this gap of the lack study that integrated MHP with PV/T system to optimize performance and increase its efficiency. The originality of the studies done by the Team on PV/T continues to contain sufficient contributions to the new body of knowledge from the international perspective since this novel the MHP-PVT has not been examined so far (Table 6 refers) despites its popularity of MHP in the electronic and telecommunication sector to remove a large amount of heat [20–24].

A novel PV/T with wide micro-channel heat pipe (MHP) was designed and constructed in this study. Experimental and numerical studies on the performance of the proposed MHP-PV/T system were carried out, and the analyzed results presented by this paper.

2. Description of novel configuration of PV/T

The materials used to build the MHP-PV/T include polycrystalline (c-Si) PV cells, aluminium micro-channel heat pipes (MHP), circular and rectangular aluminium extrusions. The MHPs were designed as