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Experimental Evaluation Of A New Design Of Heat Pipe-Based Heat Sink For Passive Cooling Of Photovoltaic Systems

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Abstract

The present experimental study focuses on the passive thermal regulation of photovoltaic (PV) systems using heat pipe-based heat sinks. The design and selection of practical and efficient heat pipe based thermal regulation systems necessitate a comprehensive understanding of the effect of using different working fluids with different charging ratios. Thus, a fabricated heat pipe with an elliptical cross section area is attached to a silicon rubber heater to imitate the heat dissipation from PV cells in heat pipe-PV systems. This single heat pipe thermal system is designed and assembled to be used with other identical pipes as a heat sink to dissipate waste heat from a PV system with the purpose of efficiency enhancement. Several sets of experiments are performed indoors to inspect the effect of using two working fluids (Ethelene and pure water), four charging ratios (50, 60, 70, and 80%) and different heat loads to mimic the absorbed energy due the incident solar irradiance received by the solar cell. Results revealed that the heat pipe filled with Ethelene as the working fluid with a charging ratio of 70 % achieves a maximum reduction in the operating temperature of PV cells when compared to pure water and other charging ratios. The current findings can open doors for further research towards the development and commercialization of novel passive cooling technology for PV systems.

Keywords: Heat pipes, PV cooling, Charging ratio, heat sink.

1. Introduction

Since oil crisis in 1970, when photovoltaics (PV) have been introduced as an innovative clean technique to convert solar irradiance directly to electric current, an extensive research has been directed to it. This significantly decreased the PV Wattage cost from 200 $ in 1970 to less than 1$ in 2016 and increased their electrical efficiency to higher than 20% compared to 2% in 1950 [1]. However, for crystalline silicon solar cells that are commonly utilized for PV systems, the output electrical power decreases by 0.4-0.5% for each 1 °C increase in their operating temperature over the characteristic power conversion temperature, 25 °C defined by manufacturers [2]. Therefore, for only 20 % of the incident solar irradiance is converted to electricity, the rest of that energy (80%) is converted to heat energy, leading to a dramatical increase in the silicon cell temperature which lessens the electrical power production [3]. Consequently, effective thermal management for photovoltaic systems is a mandatory. Many researches have investigated and introduced different cooling techniques for PV systems and they have agreed that a proper cooling method should maintain the silicon cell layer at a reduced temperature to boost the electric performance of the system, protect the system from fast degradation due to excessive thermal stresses and ensure temperature uniformity along the PV cell surface [4]. In addition, it should exhibit a low operating and maintenance costs.

The available PV cooling techniques could be generally classified to active and passive cooling techniques. Active cooling techniques are able to achieve an acceptable heat removal rate from PV cells via applying a continuous air or water flow above the PV upper or lower surfaces with the purpose of cooling [3,5]. This is accomplished by utilizing mechanical fans or pumps which necessitate electrical power from external source and in return rise the installation and maintenance costs [6]. Alternatively, passive cooling techniques are costless compared to active cooling methods, powerless operation and noiseless [7]. The focus of the current study is on passive thermal regulation by combining a heat pipe with PV systems. The heat pipe is an apparatus that allows high rates of thermal energy to flow through a considerable distance with small temperature drop via evaporation and condensation of a working fluid that fills part of the pipe. Thus, the appropriate use of heat pipe can mitigate the negative effect of excessive temperature rise in PV electrical efficiency by absorbing a large quantity of latent thermal energy during the working fluid phase change process.

A comprehensive review of the state-of-the-art applications, materials and performance of current heat pipe-based systems was conducted by Jouhara et al. [8]. The literature presented in this review specified the recent technology occurring in both high and low temperature applications along with the progression into industrial systems. They concluded that the growth of heat pipe-based systems in new waste heat recovery, temperature control and thermal management applications demonstrated a relatively short return on investment timescales. Cai et al. [9] introduced a new multi-branch heat pipe consisting of three branches (two evaporators and a condenser), which is used for the cooling of multi-heat source electronics. The experimental results revealed that the optimal working fluid filling ratio of the multi-branch heat pipe is between 75% and 100%. Moreover, a minimum total thermal resistance of 0.04 °C/W and maximum temperatures of the two evaporators were maintained below than 110 °C at a filling ratio of 75% and heating load of 160 W. Shafahi et al. [10] numerically inspected the thermal performance of cylindrical heat pipes employing a nanofluid as the working fluid to be used for passive cooling of temperature sensitive devices. Three different nanoparticles, namely Al_2O_3, CuO, and TiO_2 were used in order to improve the working fluid transport properties. They concluded that using nanofluids as the working fluid improved the thermal performance of the heat pipe and decreased the temperature gradient along it.

Numerous prior studies associated with the incorporation of heat pipes with PV systems have been conducted. Sargunanathan et al. [11] reviewed several active and passive cooling techniques of PV systems such as water spry cooling, liquid immersion cooling, heat pipe cooling and cooling with phase change material with the aim of improving the electrical performance of the commercially available PV and concentrator photovoltaic (CPV) cells. They concluded that, a 30-40 °C reduction in the solar cell operating temperature can be achieved by using heat pipe cooling. Another comprehensive review to assess some of the heat pipe systems for heat recovery and renewable applications utility was conducted by Chaudhry et al. [12]. The literature presented in this paper has shown that standard tubular heat pipe systems exhibit the largest operating temperature range when compared to other systems and thus offer viable potential for optimization and integration into renewable energy systems. Wu et al. [13] numerically investigated the thermal behavior and electrical performance of a wick heat pipe PV-thermal (PV-T) system with the aim of achieving passive and uniform cooling of solar PV cells. Results revealed that the overall thermal, electrical and energy efficiencies of the hybrid heat pipe PV-T system reached up to 63.65%, 8.45% and 10.26%, respectively under the operating conditions presented in this paper.

Although, passive thermal regulation using heat pipe was widely inspected as reported in the literature, there is still a large chance for research in their applications in PV cooling applications. Based on authors' knowledge, further experimental investigations of the emerging heat pipe-PV-T system are needed to quantify and evaluate the applicability of combining heat pipes with PV systems for cooling. In the current experiments, a fabricated heat pipe is attached to an electrical heating coil submerged in machine oil and contained in an aluminum vessel to imitate the heat dissipation from PV cells in heat pipe-PV systems. This single heat pipe thermal system is designed and assembled to be used with other identical pipes as a heat sink to dissipate waste heat from a PV system with the purpose of efficiency enhancement. Several sets of experiments are performed indoors to inspect the effect of using two working fluids (Ethelene and pure water), four charging ratios (50, 60, 70, and 80%) and different heat loads to mimic the absorbed energy due the incident solar irradiance received by the solar cell. The current findings can open doors for further research towards the development and commercialization of novel passive cooling technology for PV systems. Furthermore, the observed phenomena and obtained experimental measurements provide a pivotal source for validation of numerical approaches.

2. Experimental setup and procedures

2.1 Design and fabrication of experimental setup

The experimental setup used in the current study with the main components is schematically shown in Fig. 1(a). The employed heat pipe is fabricated from a 1 mm thick copper tube with elliptical cross section area and internal dimension of 40 mm in width, 8 mm in height, and 460 mm in length as shown in the figure. This design is achieved after machining a circular copper pipe using a pressing machine to obtain the elliptical cross section pipe which increases the contact area between PV cells and the heat pipe allowing more heat to transfer from the PV side to the heat pipe and better PV cooling is achieved. An electrical heating coil submerged in machine oil and contained in an aluminum vessel is attached to the evaporator section as shown in Fig.1 as a constant heat flux source to mimic the heat dissipation from PV cells in heat pipe PV-T systems. A temperature controller unit attached to the machine oil vessel is used to set and control the oil temperature at a constant value during each experiment. In order to attain different heat flux values, the oil temperature is varied between 40 to 90 °C in an interval of 10 °C. To facilitate charging and discharging of the working fluid, a copper valve is welded at the evaporator section as shown on the figure. Five identical fins with a rectangular cross-sectional area are located at the condenser section as heat spreaders to improve heat dissipation from the utilized heat pipe. The fins are cutted from a 0.3 mm copper sheet with dimensions of 70 mm in length and 30 mm in width for each and then a window profile with the same dimensions of the employed heat pipe is made at the center of each fin to facilitate the assemble process. Epoxy is used to fill the gaps between fins and the heat pipe to ensure good contact between them. For insulation, a 50 mm thick glass wool sheet (k = 0.04 W/mK) is used on all sides of the evaporator and heating coil with the aim of minimizing heat losses to the environment. However, the condenser and adiabatic sections are kept without insulation and exposed to the ambient.

Seven calibrated K-type thermocouples, of 0.4 mm bare wire diameter are used for temperature measurements. Three thermocouples (T_1, T_2, and T_3) are situated at the evaporator section, while two thermocouples (T_4, and T_5) are located at the adiabatic section. The remaining thermocouples (T_6, and T_7) are placed at the condenser section as shown in Fig. 1(b). A temperature readout is utilized to record the temperatures of thermocouples. In the current study, two working fluids (Ethelene and pure water) with four charging ratios (50, 60, 70, and 80%) are experimentally investigated. Table 1 lists the thermo-physical properties of the utilized working fluids.

Table 1
Thermo-physical properties of pure water and Ethelene.

	Boiling point (°C)	Density (kg/m^3)	Latent heat of vaporization (kJ/kg)
Pure water	100	1000	2256
Acetyl Alcohol	78	789	846

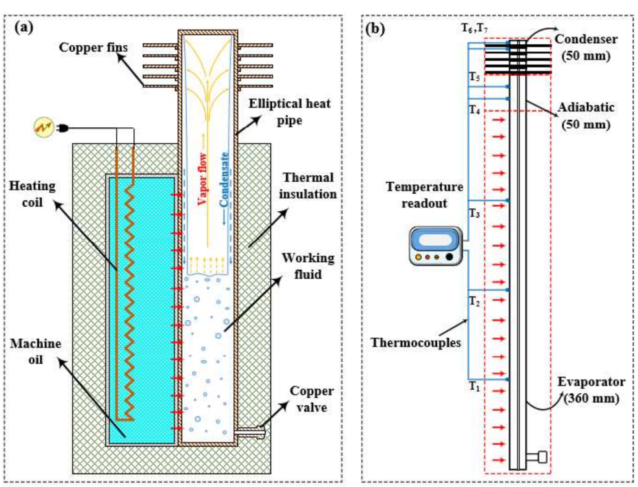

Fig. 1 (a) Schematic diagram of the experimental setup and (b) The highlighted thermocouples locations.

2.2 Experimental procedures and data reduction

Initially, the employed heat pipe is vertically rotated to keep the copper valve (evaporator) at the upper side of the heat pipe. Then, the working fluid is charged inside the heat pipe at the atmospheric pressure through the copper valve until reaching the required charging ratio which is the ratio between the working fluid volume to the heat pipe volume. Subsequently, the pipe is heated until reaching to 100 °C to ensure the phase transition of the working fluid. Later, the valve is partially opened to allow air and other gases to be expelled outside the pipe by the vapor of the working fluid. This is maintained until observing vapor leakage from the valve which confirms that the working fluid (liquid + vapor) completely filled the heat pipe. At that moment, the valve is perfectly closed, and the pipe is leaved to cool until reaching to the desired initial conditions. During experiments the heat pipe is fixed at an inclination angle of 30° to simulate the orientation of the heat pipe-PV system in real applications. Moreover, the heat pipe is rotated to keep the evaporator section at the lower side and condenser section at the upper side as shown in Fig. 1 to facilitate heat dissipation to the environment.

All tests are performed indoors in an air-conditioned space where it is possible to control the ambient temperature value. At the onset of each experiment, all working fluids are initially at a uniform temperature of 25 °C (liquid phase) while the laboratory temperature is kept at 26±2 °C during the whole experiments. The experiments are started by rising the oil temperature to the desired temperature via supplying power to the heating coil. The experiments are continued until the thermocouple's temperatures (T_1 to T_7) reached to the steady state. In the current study, several sets of experiments are accomplished to examine the effect of using two working fluids (Ethelene and pure water), four different charging ratios (50, 60, 70, and 80%) and six different oil temperatures (50 to 90 °C in an interval of 10 °C) to mimic the absorbed energy due the incident solar irradiance received by the solar cell. Each stage of experiment is repeated to verify the measurement accuracy and attain the required reproducibility of the results. The obtained results are compared, and the deviation is found to be insignificant.

In order to estimate the heat transferred per unit area from the machine oil to the evaporator wall by free convection, [14]. The following equations can be used:

$$q''_{add} = \frac{k}{L}\overline{NU}\left(T_{oil} - T_{Evap.}\right) \qquad (1)$$

The average Nusselt number on the inclind evaporator wall is estimated by:

$$\overline{NU} = 0.68 + \frac{0.67 Ra_L^{1/4}}{\left(1+\left(0.492/\Pr\right)^{9/16}\right)^{4/9}} \quad when, \quad Ra_L \le 10^9 \quad or \tag{2}$$

$$\overline{NU} = \left(0.825 + \frac{0.38 Ra_L^{1/6}}{\left(1+\left(0.492/\Pr\right)^{9/16}\right)^{8/27}}\right)^2 \quad when, \quad Ra_L > 10^9 \tag{3}$$

$$Ra_L = \frac{g\cos\theta\,\beta\left(T_{oil} - T_{Evap.}\right)L^3}{\alpha\,\upsilon} \tag{4}$$

where, q''_{add} is the heat added to the evaporator section per unit area (W/m^2); $\overline{NU}$ is the average Nusselt number; L is the characteristic length; k, α, v, Pr and T_{oil} are the machine oil thermal conductivity (W/mK), thermal diffusivity (m^2/s), kinematic viscosity (m^2/s), Prandtl number and temperature (°C), respectively. Finally, Ra_L, g, θ, β and $T_{Evap.}$ are the Rayleigh number, gravitational acceleration (m/s^2), heat pipe inclination angle, expansion coefficient and the evaporator average temperature (°C), respectively.

The total thermal resistance of the heat pipe, R_{th} (°C/W) is defined as the ratio between the difference in the average temperature of the evaporator and condenser sections to the power input. It can be calculated as:

$$R_{th} = \frac{\left(T_{Evap.} - T_{Cond.}\right)}{Q_{add}} \quad and \quad Q_{add} = q''_{add} \times A_{Evap.} \tag{5}$$

where, Q_{add} is the rate of heat added to the evaporator (W), T_{Cond} is the condenser average temperature (°C) and A_{evap} is the contact area between the evaporator section and the heating unit (m^2).

A generic polycrystalline solar cell comprises of five layers; a glass cover, a polycrystalline silicon solar cell, ethylene vinyl acetate (EVA) upper and lower layers, and a TPT (Tedlar/PET/Tedlar) back sheet layer is commonly utilized for PV applications [15]. In the current study, the PV cell steady state temperature, T_{PV} can be calculated using the following equation as a function of the evaporator average temperature and the rate of heat added per unit area [16].

$$T_{PV} = T_{Evap.} + q''_{add}\left(\frac{\delta_{sc}}{k_{sc}} + \frac{\delta_{EVA}}{k_{EVA}} + \frac{\delta_T}{k_T}\right) \tag{6}$$

where, δ_{sc}, δ_{EVA} and δ_T are the thickness of silicon solar cell layer, EVA layer and TPT back sheet layer (m), respectively. Moreover, k_{sc}, k_{EVA} and k_T are the thermal conductivity of silicon solar cell layer, EVA layer and TPT back sheet layer (W/mK), respectively.

3. Results and discussions

Thermal management of PV systems using heat pipes is influenced by the thermal behavior of the utilized working fluid. Thus, the design and selection of practical and efficient heat pipe based thermal regulation systems necessitate a comprehensive understanding of the effect of using different working fluids with different charging ratios. In the current experiments, the fabricated thermal system is attached to an electrical heating coil submerged in machine oil and contained in an aluminum vessel as previously stated to imitate the heat dissipation from PV solar cells. The local temperature distribution of the heat pipe at seven different locations are logged throughout the experimental run. The effect of using two distinct working fluids (Ethelene and pure water), four different charging ratios (50, 60, 70, and 80%) and six different oil temperatures (50 to 90 °C in an interval of 10 °C) corresponding to different heat flux values are experimentally investigated.

3.1 Thermal characterization of the heat pipe-based heat sinks for PV thermal regulation

The rate of heat added per unit area (q''_{add}) to the evaporator section is calculated based on Eq. 1 and illustrated in Fig. 2 at different oil temperatures for different working fluids and various charging ratios. Based on the figure, some important observations can be made. As expected, rising the oil temperature significantly increases the heat added to the evaporator section and this trend is true at all working fluids and charging ratios. For instance, at a charging ratio of 80% (Fig. 2(d)) increasing the oil temperature from 50 to 90 °C, rises the rate of heat added per unit area from about 148.5 to 2704.85 W/m^2 and from 262.75 to 3263.3 W/m^2 for pure water and Ethelene, respectively. Moreover, it can be observed that at all charging ratios and oil temperatures, the heat absorbed by Ethelene is much higher than that using pure water. For example, at a charging ratio of 80%, the difference in the absorbed heat by Ethelene and that by pure water is around 114, 338 and 559 W/m^2 at oil temperatures of 50, 70 and 90 °C respectively. This thermal behavior is mainly attributed to the dissimilar thermo-physical properties of the two working fluids. As previously cited in Table 1, the boiling point and latent heat of vaporization of Ethelene is lower than those of the pure water which means that Ethelene starts to vaporize earlier than pure water under the same operating conditions. Accordingly, Ethelene is capable to absorb both sensible and latent heats while water absorbs only sensible heat at the applied heat loads in the current study. In addition, changing the working fluid charging ratio slightly affects the cooling performance of the heat pipe. However, the maximum absorbed energy is attained at a charging ratio of 70% using Ethelene as the working fluid and at an oil temperature of 90 °C. Finally, it is worth to mention that the higher value of the rate of heat added per unit area, refers to a better cooling performance of the heat pipe-based heat sink and subsequently a lower PV temperature. Therefore, Ethelene working fluid has more preference than pure water when using heat pipe PV-T system for practical applications.

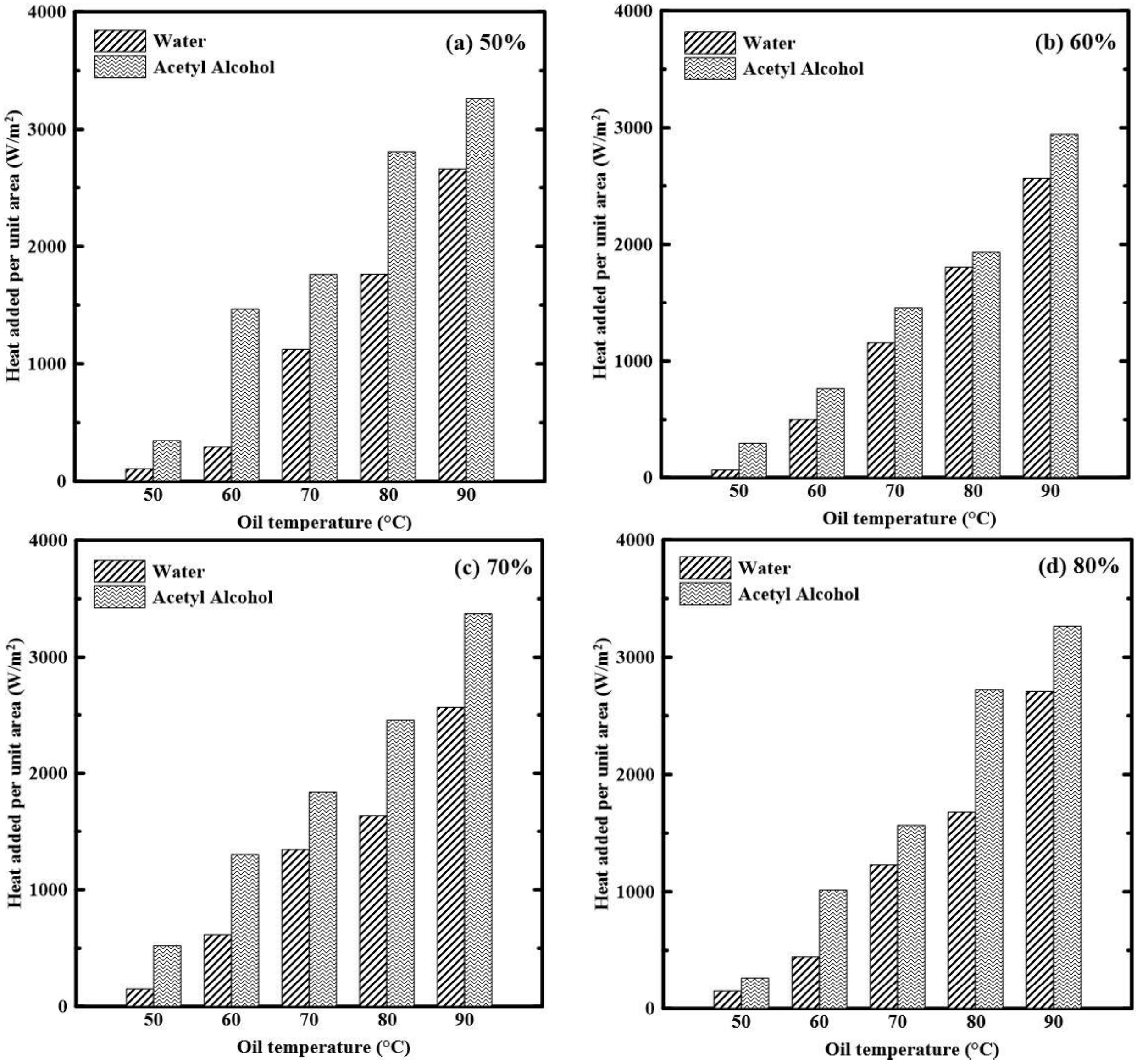

Fig. 2 Variation of the rate of heat added per unit area to the evaporator section with different oil temperatures at different working fluids for different charge ratios.

For further verification, the total thermal resistance of the heat pipe, R_{th} (°C/W) is calculated using Eq. 5 for the two working fluids at different charge ratios and presented in Fig. 3 as a function of the oil temperature. Comparing different values of the heat pipe total thermal resistance under different operating conditions is important to evaluate its performance during the heat transfer tests. In this section the lower value of, R_{th} indicates small resistance to heat flow through the pipe and consequently a higher efficiency of the system. Based on the figure it is revealed that rising the oil temperature (heat flux) results in the total resistance of the heat pipe to be reduced for both Ethelene and pure water. Additionally, employing Ethelene as the working fluid attains a lower values of the heat pipe total thermal resistance when compared to pure water and this is true at all charging ratios and oil temperatures. However, the difference in the total resistance between Ethelene and pure water at any charging ratio is decreased by increasing the oil temperature as shown in the figure. It is also obvious that the effect of varying the charging ratio on R_{th} is more pronounced at the lower oil temperatures such as 50 and 60 °C, while this effect is insignificant at the higher oil temperatures starting from 70 °C. As a final point, the charging ratio of 70% achieved the minimum total thermal resistance compared to other values for both Ethelene and pure water, especially at an oil temperature of 90 °C. Therefore, Ethelene is suggested to be used as the working fluid for heat pipe PV-T systems as previously mentioned with a charging ratio of 70% to attain the best system performance.

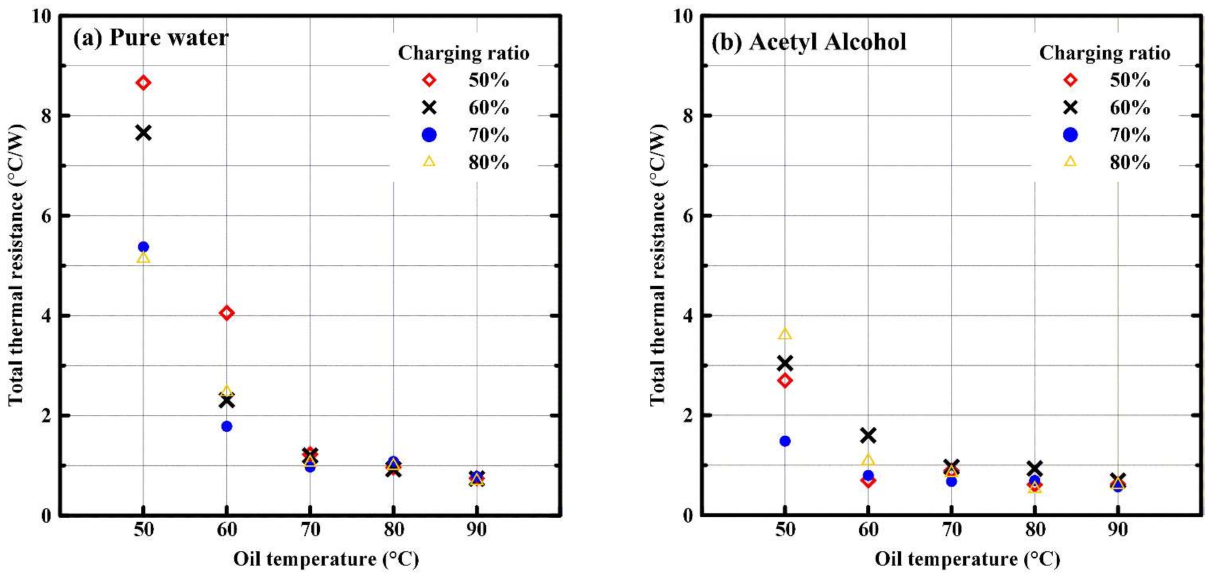

Fig. 3 Variations of the total thermal resistance of the heat pipe as a function of the oil temperature for different working fluids at different charge ratios.

3.2 The Photovoltaic cell performance

The steady state average temperature of the evaporator section associated with the operating temperature of the PV cell is the key parameter to evaluate the cooling performance of heat pipe-based heat sinks and understand how the heat pipe could be employed as a passive cooling technique. Therefore, the average temperature of the evaporator section is calculated based on the measurements of the three thermocouples (T_1, T_2 and T_3) attached to the evaporator wall as shown in Fig. 1(b). Afterward, the corresponding PV cell temperature is calculated using Eq. 6 and the obtained results are compared and presented in Fig. 4. The figure illustrates the PV cell steady state temperature as a function of the oil temperature for different working fluids at different charge ratios. Based on the figure, it is clearly shown that increasing the heat load, considerably rises the PV cell temperature for both working fluids due to the increased amount of thermal energy absorbed by the PV cell and consequently by the evaporator section. However, utilizing Ethelene as the working fluid successfully maintained the PV cell at a lower temperature when compared to pure water and this trend is true at any charging ratio and oil temperature as shown in the figure. This enhancement is mainly attributed to the larger amount of thermal energy absorbed by heat pipe using Ethelene and the lower total thermal resistance when compared to that using pure water as previously revealed in Figs. 2 and 3. For additional verification, the obtained temperature reduction using Ethelene can be translates to an increase in the PV systems output power. This is accomplished by assuming the temperature coefficient of maximum power point as -0.5 %/°C [2] which means that every 2 °C reduction in the PV operating temperature will theoretically result in a 1 % increase in the output power. Table 2 presents the PV temperature difference, ΔT between the system using Ethelene and that using pure water and the percentage of output power increment, ΔP_{elec} due the temperature reduction. The obtained results further prove the advantages of employing heat pipes partially filled with Ethelene working fluid as an operative passive cooling method for PV systems.

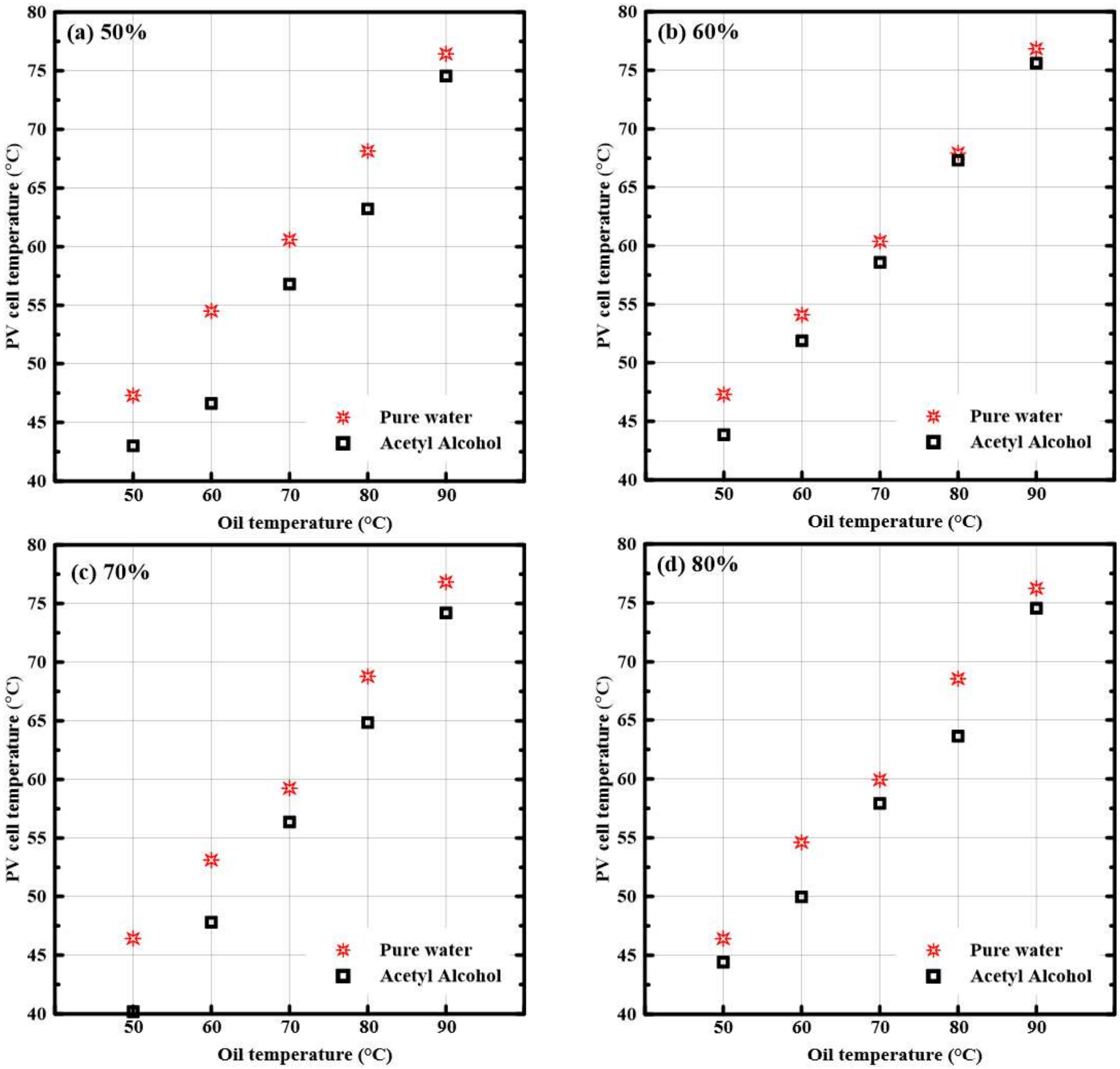

Fig. 4 Variations of the PV cell steady state temperature as a function of the oil temperature for different working fluids at different charge ratios.

Table 2
PV temperature difference, ΔT between the system using Ethelene and that using pure water and the percentage of output power increment, ΔP_{elec} due the temperature reduction.

	50 °C		60 °C		70 °C		80 °C		90 °C	
	ΔT (°C)	ΔP_{elec} (%)	ΔT (°C)	ΔP_{elec} (%)	ΔT (°C)	ΔP_{elec} (%)	ΔT (°C)	ΔP_{elec} (%)	ΔT (°C)	ΔP_{elec} (%)
50 %	4.29	2.14	7.8	3.9	3.8	1.9	4.9	2.45	1.89	0.94
60 %	3.43	1.71	2.22	1.11	1.8	0.9	1.62	0.81	1.22	0.61
70 %	4.23	2.11	4.32	2.16	2.87	1.45	3.9	1.95	2.63	1.315
80 %	1.998	0.999	4.66	2.33	2.1	1.05	4.9	2.45	1.69	0.845

Conclusions

This study presents an experimental evaluation of the applicability of integrating heat pipes with photovoltaic systems for passive thermal regulation. Several sets of experiments are performed indoors to inspect the effect of using two working fluids (Ethelene and pure water), four charging ratios (50, 60, 70, and 80%) and different heat loads to mimic the absorbed energy due the incident solar irradiance received by the solar cell. It can be concluded that using Ethelene as the working fluid with a charging ratio of 70 % achieves a maximum reduction in the evaporator temperature which consequently translates to best performance of PV cells and this is true at any heat load. The current findings can open doors for further research towards the development and commercialization of novel passive cooling technology for PV systems.

Nomenclature

G	Gravetional acceleration (m/s^2)
K	Thermal conductivity (W/mK)
L	Characterstic length (m)
$\overline{NU}$	Average Nusselt nymber
Pr	Prandtl number
PV	Photovoltaic
q''_{add}	Heat added to the evaporator section per unit area (W/m^2)
Ra	Rayleigh number
R_{th}	Total thermal resistance of the heat pipe (°C/W)
T	Temperature (°C)

Greek symbols

Α	Thermal diffusivity (m^2/s)
Β	Expansion coefficient (1/K)
V	Kinematic viscosity (m^2/s)
Δ	thickness [m].
Ɵ	Inclination angle

Subscripts

Cond	Condencer
elec	Electrical
EVA	Ethylene vinyl acetate layer
Evap	Evaporator
Sc	Silicon cell layer
T	Tedlar
Th	Thermal

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