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Evaluation of an Integrated Pipe Water Cooling Strategy to Improve BIPV Structure Performance

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1. Abstract

When the temperatures of photovoltaics break a threshold of 25 degrees celsius, they begin to lose efficiency. This work describes the basis of a water cooling mechanism which may be used to cool down roof mounted photovoltaics. After a thorough literature review, it was decided that running water through aluminum pipes attached to the back of a solar panel would be the most effective method. To study the effectiveness of such a system, a prototype was fabricated two panels were brought out to the top of a solar deck in an engineering university building and laid out in parallel. One panel had the cooling system attached to its back and the other one had no attachments to serve as a control panel. Experimentation was performed by taking temperature measurements for one hour before activating the hydraulics for 30 minutes. It was found that a significant reduction of temperature occurred on the water-cooled panel.

Keywords: *Solar power, buildings, thermodynamics, cooling,*

2. Introduction

With the advent of global climate change, human civilization will have to plan for the future and overhaul existing critical infrastructure with sustainability and resilience in mind. A key element to this will be the deep decarbonization of the energy sector. One of the most promising technologies is the deployment of rooftop solar panels, known in many technical circles as Building-Integrated Photovoltaics. However, the performance of these systems are not immune to ambient environmental conditions. In particular, it has been found that with every degree centigrade above 25 C(Pillai et. al) the electricity efficiency decreases by upwards of 0.5%. This will be especially harmful to communities who inhabit hotter climates and the global south, where the intensity of the sunlight is much greater.

These issues can be greatly mitigated through the application of cooling techniques to solar panels. By enabling solar energy generation to operate at a lower temperature, efficiency can be greatly improved. This will

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assist areas with warm ambient climates in implementing distributed energy resources and transition to a carbon free economy.

3. Literature Review

Before deciding on a specific technology, a literature review was undertaken.

3.1 Liquid Immersion

Liquid immersion consist of solar panels being immersed in a thin layer of a liquid to maintain lower temperatures. Liquids such as non-polar silicon oil, polar ethanol, glycerin, non-polar benzene, inorganic distilled water, and tap water have been tested, with some being more effective than others.

The performance of bare cells and a solar panel were examined with different liquids immersed at different depths by Abrahamyan et al (2001). It was determined that bare solar cells immersed in non-polar silicon oil performed the best. The cells increased their efficiency by 4.07% while immersed at 9 mm, compared to a 3.78% and 3.49% efficiency at 3 and 6 mm, respectively. At wide temperature ranges, silicon oil has a high chemical stability, good weather resistance, and has low surface tension. These physical and chemical performances make silicon a good candidate for high temperature and long service applications. Although, silicon-oil might be an alternative to keeping solar panels cool, the cost of this liquid is not economical. One of the goals of this project is to provide a cost-effective cooling system for solar panels, therefore this method would not meet this goal.

Rosa-Clot et al. (2010) compared the performance of three photovoltaic panels, two of which were immersed at 4 cm and 40 cm in water and one that was at ambient temperature. According to Rosa-Clot et al. there are two main effects that increase the efficiency of a commercial panel placed in water, the first is the reduction of light reflection and secondly, the absence of thermal drift. Thermal drift refers to the change in the normal operational behavior of a device due to changes in ambient temperature. It was concluded that the efficiency increased or reduced depending on the depth the photovoltaic panel was immersed in, as shown below in Fig. 1.

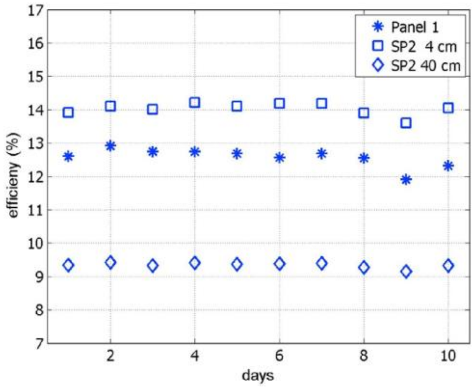

Figure 1: Comparison of the three photovoltaic panels in different ambients all tested for a period of 10 days (Rosa-Clot et al.(2010))

3.2 Phase-Changing Materials

Phase-Changing Materials (PCMs) are materials which are at the interphase point in ambient temperatures. This allows them to absorb large amounts of latent heat before changing their temperature, making them extremely effective as passive heat skins.

These properties have made PCMs a captivating topic for numerous researchers. A one-dimensional heat transfer model usable for simulation was developed for combined PV-PCM systems (Kibira 2016). This was further expanded upon in later work with the creation of a two-dimensional heat transfer model for the system but also

empirically evaluated the effectiveness of a PCM system with different fin configurations (Huang et. al 2018). Adding fins were also shown to be beneficial of the PV system (Khanna et. al (2018)) (Ma. et.al (2015)).
Field testing for the economic effectiveness of PV-PCMs in Ireland and Pakistan was carried out by Hasan et. all which revealed that PV-PCM systems were economically in hot climates similar to the latter but ineffective in the former's (Hasan et. al 2014). Since San Jose's mild temperature norms puts in in the middle of the aforementioned areas, it would very likely be at the breakeven cost point. A list and testing of five possible PV-PCM materials was also compiled (Hasan et. al. 2010). Ultimately, the high initial cost of PCMs outweighed their utility and made them unsuitable for our study. After obtaining the cost of materials and possible efficiency in a mild climate, it did not appear effective for utilization.

3.3 Water Trickling

Another promising cooling strategy is to utilize water trickling down the front surface of the panel. This will not only cool down the panel itself by also clean it up ony residue, thereby increasing its efficiency. Work by Schiro et. al. (2017) found that a uniform spreading of water would achieve the greatest results.

4. Design

4.1 Theory

The cooling system design selected worked as follows. Water is passed through a series of horizontal square aluminum pipes attached to the back of a solar panel. The flowing water absorbs heat from the panel, thereby cooling it. The heated water at the end is either discarded or recycled depending on the setup of the system. Since the literature stated that the optimal temperature for solar panels was 25 degrees celsius, that became the target temperature for the system.

4.2 Setup

The systems design can be seen in Fig. 2**.** The cooling system uses PVC as the inlet for water flow. Clear acrylic tubing would then connect the PVC to square aluminum pipes. These pipes are attached to the back of the PV panel using thermal paste. Water exits the aluminum pipes, through acrylic tubing and out through PVC.

The component descriptions are listed below.

Component	**Description**
Rectangular Aluminum Pipe	8 - 1”x1”x48”
PVC Clear Vinyl Tube	7/8 in. O.D. x 5/8 in. I.D. x 10 ft.
PVC Schedule 40 Plain-End Pipe	1 in. x 10 ft.
Tube Heat Sink Compound	3 oz.
Heavy Duty Duct Tape	1-7/8 in. x 13.2 yds.

Tab. 1 - System components

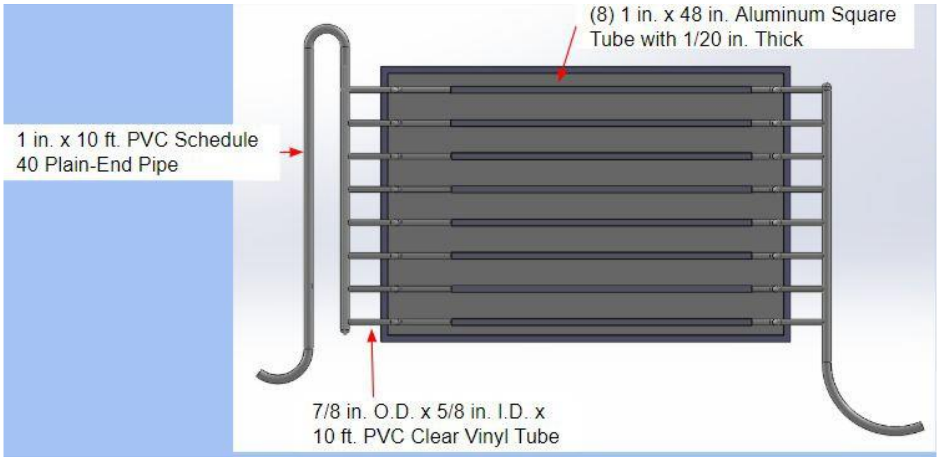

Figure 2: Design of Cooling System

4.3 Physical Implementation

Implementation of system designed is shown in Fig. 3.

Fig 3 - Implemented system

5. Experimentation

5.1 Setup

For the experiment, a triple Sunpower SPR-320E-WHT-D 320W Solar PV panel rack oriented south-west were used for the base model. The front panel was laid out horizontally such that it was parallel to the middle panel. The front panel had the cooling system attached while the middle was used as a control panel. This was done so each panel would receive equal irradiation and therefore have identical temperature signatures before any cooling was applied, allowing for a more objective analysis of the system performance. The solar panel rack came with a host of other solar PV system components such as charge controllers and a battery. This setup can be seen in Fig. 4, with the cooled panel overlaid in blue and the base panel in red.

Figure 4 - The Solar Rack Setup

5.2 Tools

14 T-type thermocouples with an accuracy of +- 0.1 C were used to carry out temperature measurements. These were spread across the back of the PV panel parallel to one another to obtain surface temperature readings. The back of the panel was chosen since it would be the closest to the proposed piping system. The position of each thermocouple can be seen in Fig. 5. These were connected to an Agilent 34970a DAQ System with a sampling rate of one reading per minute.

Three 3 LI-COR - LI-200SA Pyranometers were used to measure the incident irradiation on the solar panels. These were placed on the top of the front-facing solar panel in the rack (two on each end and in the middle) and connected to a three-channel Li-Cor 1500 Logger.

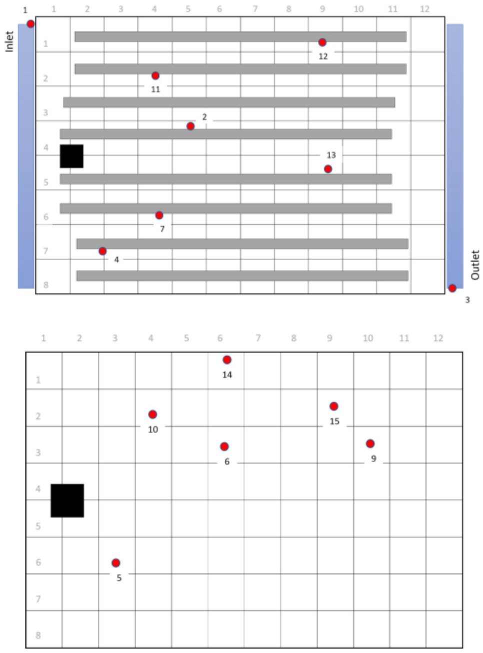

Figure 5: Map of backside thermocouples. The numbers correspond to the thermocouple on the DAQ system

5.3 Procedure

The testing procedure was straightforward. At around 1:30 pm on April 24th 2019, the thermocouple loggers were activated. These would take data at a rate of one sample per minute for an hour before the water pump was switched on. Data would be taken for another 30 minutes. From this, It can be seen not only the effect of water on panel temperatures but also how it compares to a panel which receives no applied cooling

5.4 Results

The results from experimentation can be seen in Fig 6. Once water cooling was activated, the solar panel with the system attached was able to experience a drastic temperature drop along with the inlet and outlet water temperature. The minimum average temperature at the back panel with cooling after activation was 36.9 degrees C, compared to 48.9 degrees C for the control panel, even though it was at a higher temperature before activation. The minimum average temperature was 32.4 degrees C, which is 7.4 degrees higher than the desired temperature of 25 degrees C. It is important to note that the ambient temperature at the day of experiment was 32.2 C (Weather San Jose CA 95112 April 24th 2019. (2019, April 24)), making it extremely difficult to achieve the desired temperature of 25 degrees C. Surprisingly outlet water temperature was only slightly higher than the inlet temperature. This indicates that due to higher thermal conductivity of aluminum the heat was dissipated from water through aluminum structure.

As seen in Fig. 7, the irradiance over time was fairly constant. As there was no significant change in irradiation, the results should not have been affected too drastically.

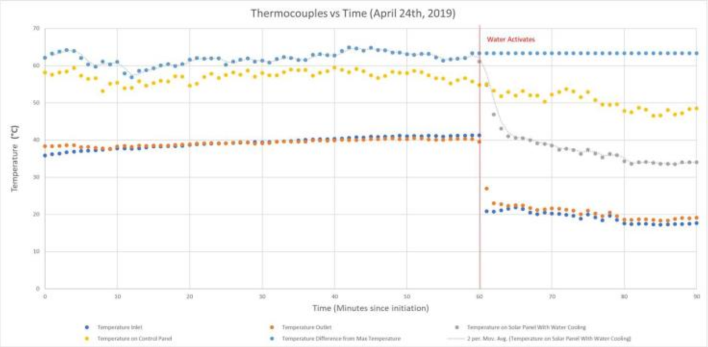

Figure 6: Thermal data over the period of the experiment

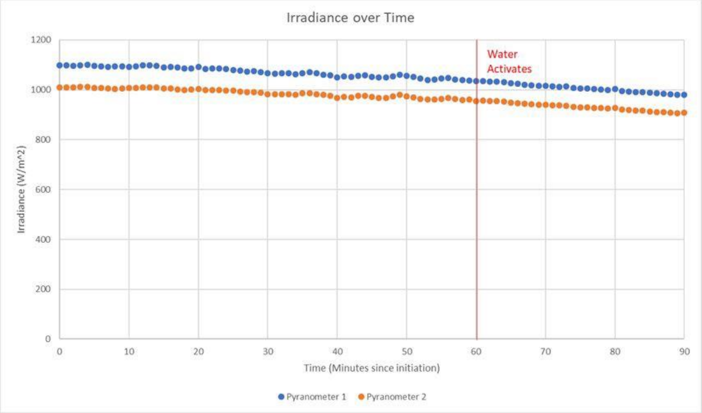

Figure 7: Irradiance data over the period of the experiment

6. Thermal Analysis

Theoretical calculations were needed to compare both the experimental and simulation results. The point of interest was the panel’s back surface temperature to compare to readings given by the thermocouples. To obtain this temperature a thermal resistance network needed to be analyzed. Thermal resistance of the solar panel, or any other medium, depends on its geometry and thermal properties. In this case, the thermal resistance of the panel was assumed to be in series, with the map seen in Fig. 8. Therefore, the equivalent thermal resistance is determined by adding the individual resistances, **Eq (1)**. Basic knowledge about the following parameters must be known: ambient temperature, wind velocity, and irradiation at the time of the experiment for all boundary conditions. Other parameters needed to be calculated for the set up were the convection coefficients and the total heat resistance of the panel without and with the cooling system.

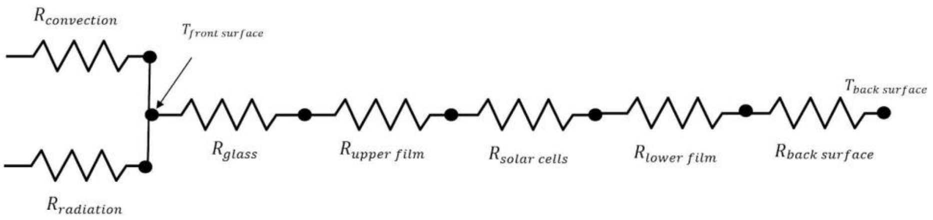

Figure 8 - Thermal Resistance Network

$$R_{total} = R_{conv\ and\ rad} + R_{glass} + R_{upper\ film} + R_{solar\ cells} + R_{lower\ film} + R_{back\ surface}\ [\frac{^\circ\mathrm{C}}{W}] \quad (1)$$

Where resistance R_{conv} , R_{cond} , R_{rad} for each material are the following.

$$R_{conv} = \frac{1}{hA_s}\ [\frac{^\circ\mathrm{C}}{W}] \quad (2)$$

$$R_{cond} = \frac{L}{kA_s}\ [\frac{^\circ\mathrm{C}}{W}] \quad (3)$$

$$R_{cond} = \frac{1}{h_{rad}A_s}\ [\frac{^\circ\mathrm{C}}{W}] \quad (4)$$

As seen from the thermal resistance network, most solar panels consist of five thermal conductive materials which are the anti-reflective glass, the upper encapsulating film (EVA), solar cells, the lower encapsulating film (EVA), and the tedlar laminated film (back surface). Thermal conductivity and thickness of each material, and surface area of the solar panel, were needed to determine individual thermal resistances, and eventually the equivalent resistance. Temperature of the back surface can be determined if the heat transfer, Qdot, and the ambient temperature are known, **Eq. (5)**.

$$\dot{Q} = \frac{T_{back\ surface} - T_{ambient}}{R_{total}} \quad (5)$$

From the equation above it is notable that the rate of heat transfer between the two surfaces is equal to their temperature difference divided by the total thermal resistance of the solar panel.

Using Equations 1-5, a back surface temperature of 58.2 ℃ was determined. Comparing this result to the highest temperature read by the thermocouples, 59 ℃, there is a percent error of about 1.4.

7. Conclusion and Future Work

7.1 Conclusion

A proposed water cooling system for building-integrated photovoltaics was developed and manufactured. Through experimentation, we were able to validate that it was able to provide effective cooling for a solar panel. The minimum average temperature at the back panel with cooling after activation was 36.9 degrees C, compared to 48.9 degrees C for the control panel. The minimum average temperature was 32.4 degrees C, which is 7.4 degrees higher than the desired temperature of 25 degrees C.

It is important to note that the ambient temperature at the day of experiment was 32.2 C, making it extremely difficult to achieve the desired temperature of 25 degrees C. Surprisingly, outlet water temperature was only slightly higher than the inlet temperature. This indicates that due to higher thermal conductivity of aluminum the heat was dissipated from water through aluminum structure.

7.2 Future Work

Future work on this project should concentrate on shifting the system to a passive cooling solution, where no active energy input needs to be used. This can be accomplished through heat pipes and natural heat sinks. In addition, one of the chief priorities for the system redesign should be to make it such that it can be commercially implementable into a building. This will enable the technology to be dispersed throughout the world and assist in achieving deep decarbonization. Regarding the CFD simulation, future work on this regard would consist on using the ANSYS thermal calculator to obtain more accurate irradiation data rather than data obtained from the pyrometer.

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