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Hydrogels beads for Cooling Solar Panels: Experimental Study

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Abstract

This paper aims to present a new and novel experimental study for the usage of hydrogel beads with different bed configurations as a cooling attachment underneath solar panel. Four different bed configurations were studied using different layers and fins arrangements then compared with the un-cooled system. The best results were obtained using 3 rows of hydrogel beads with fins where the panel temperature dropped by approximately 10 ˚C below the un-cooled panel at 1000 W/m^2 (representing around 14% temperature drop comparing to the panels' initial temperature) leading to an increase in the electricity generation efficiency of 7.2 % compared with the un-cooled system.

Keywords: evaporation, Solar panels, cooling, materials, Hydrogel, saturated

1. Introduction

Energy efficiency is one of the major goals to be achieved and optimised in any engineering processes. According to the latest statistics announced by International Energy Agency (IEA) [1]…'Energy efficiency investment is defined as the percentage expenditure on new efficient energy technologies that reduce the energy usage or increase the energy production by updating the production equipment'. The global investment in energy efficiency sector recorded an overall expenditure of 240 billion USD in 2018. Moreover, the world energy demand increased by 2.3% in 2018 which is nearly twice the average annual rate since 2010. Renewable energy is one of the best solutions for environmentally friendly production systems. Solar energy, wind energy, geothermal energy and hydro energy are developing more and more over years. Renewable energy share is also increasing steadily and is estimated to reach 21% of the total consumption in 2020 as reported by European Environment agency [2]. A comparison between different types of electricity generation technologies was done by Piyush Choudhary, Rakesh Kumar Srivastava in [3]. They reported that solar energy recorded the least impact to the environment with an expected lifetime of 25-30 years. Silicon crystalline solar panels reached an efficiency of 24.4% in laboratory conditions only. On the other hand, commercial panels do not exceed 21% -value reached only by super monocrystalline panels- and are more expensive to install [4].

Thermal regulation of solar panels has attracted many researchers over the last 4 decades because of the negative effect of the temperature increase on the solar panel electrical performance. Qais Mohamed Aish [5] reported that the polycrystalline solar panels have a power loss factor of 0.49%/˚C and 0.54%/˚C for monocrystalline panels. The research on solar panels temperature control involved using either an active or a passive cooling system. The active cooling system involving forcing a fluid over the bottom or the top surface of the panel used part of the energy produced by the system, hence decreasing the energy efficiency [6]. As for the passive system, it is the latent heat of different materials which is used for heat extraction and no usage of energy produced.

Phase Change Materials (PCM) of high latent heat capacity were studied and reviewed by Waqas A. et al. [7]. They observed that using PCMs as a cooling agent for solar panels can reduce the temperature up to 20˚C -depending on the meteorological conditions- which can lead to efficiency increase up to 5%. They also concluded that, around 2.6 kg of PCM is required per one-meter square of solar panels to reduce its temperature by 1˚C which increases the total weight by 40%.

Heat pipes were also studied for cooling solar panels and reviewed in [8] and estimated that heat pipes can reduce the temperature of solar panels to 32˚C with a surface temperature uniformity of 3˚C. Passive cooling using fins was also studied by Grubišić-Čabo, F et al. [9]. They studied two different rib configurations for cooling solar panels. Their system showed about 2% electricity generation increase throughout the study period. Soliman, A. M. A [10] experimentally investigated the electric performance of photovoltaic panels with a heat sink cooling system. Their results indicated that using passive air to cool the heat sink decreased the panel temperature by 5.4%.

The cooling effect of direct liquid immersion for concentrated solar panels at 9.1 suns concentration was studied by Sun, Y el al. [11]. Results showed that the temperature of the panel was uniform over time within the range (20-31)˚C at 910 W/m^2 radiation, and no degradation in the panel efficiency was detected after 270 days.

Wind induced convection was studied at different wind speeds with varying wind channels variation under the panel [12]. The absolute resultant efficiency was increased by 1 to 2 % in relation to the channel geometry and the radiation intensity.

F.Arpino et al. [13] proposed a combined experimental and numerical study over the different geometrical design parameters including, thickness of the aluminium frame, installation technique, and environmental operating conditions. They concluded that there is an optimal distance of the panel from support to maximise the performance. Al-Nimr, M. A et al. [14] presented a novel hybrid photovoltaic thermoelectric system for cooling distillation systems. The proposed system was able to give demand electricity and water as well. The system overall efficiency was 57.9% with PV panel efficiency of 12.32%.

Abdallah, S. R. et al. [15] proposed a new thermal regulation technique for commercial solar panels depending on the water desorption phenomena using water absorbent substances. Activated alumina (Zeolite) was tested under different radiation intensities with different system configurations. Their results indicated that the system was able to reduce the panel temperature by 9˚C compared to un-cooled solar panel, increasing the electrical efficiency by 7% compared to the generating electrical efficiency of the stand-alone solar panels.

New materials implantation is still considered as the most promising way forward for further investigation in cooling solar panels research. Passive cooling can achieve better temperature regulation if the attached substance for cooling has high thermal characteristics E.g. thermal conductivity, latent heat and specific heat. According to Science of Changing World website, water counts 71% of the total coverage of the Earth's surface [16]. It also has a relatively acceptable thermal characteristics to be used as an effective cooling agent for solar panels [17]. Hydrophilic gels, which are commercially called hydrogels, are promising substances for applications that required thermal regulation or hydration over a long period. Their capacity to store water, smartness and thermal characteristics are making hydrogels unique materials for this purpose [18, 19]. Their ability to store a high amount of water (up to 800%) of their original weight comes from the hydrophilic functional group attached to the backbone of the polymer and have a specific shape because of cross links between the network chains [20]. These hydrogels are widely used in agriculture as they are cheap and have a high ability to hold water, making them very sought after in water irrigation and with fertilisers [21]. These substances have a lot more usages than for agricultural purposes. They are also used for issue engineering in biomedical applications [22]. Koo H-J. et al. [23] studied on the microscale the embedded hydrogel PV cell for reducing light driven degradation of photovoltaic molecules on chemical. The studied wavelength was 320-500 nm at 1.5 AM solar radiation of 1000 W/m^2 with a single block of hydrogel with different P-H.

This paper aims to first propose hydrogels as a heat removal agent from the back surface of solar panels, hence reducing their temperature and increasing their electricity generation. Worth mentioning that hydrogels were not studied before for thermal regulation applications on engineering scale and this is the main novelty of this study. The system depends mainly on water desorption cooling technique proposed in [15] which includes three main steps. The first step is the heat diffusion through the hydrogel bed beneath the solar panel, the second step is water desorption in form of water vapour that escape carrying the un-wanted heat from the system. The last step is to cool down the solar panel by more water desorption and heat removal as presented in figure 1. It could be noticed that in the last step, the hydrogel beads size reduced as the water evaporates.

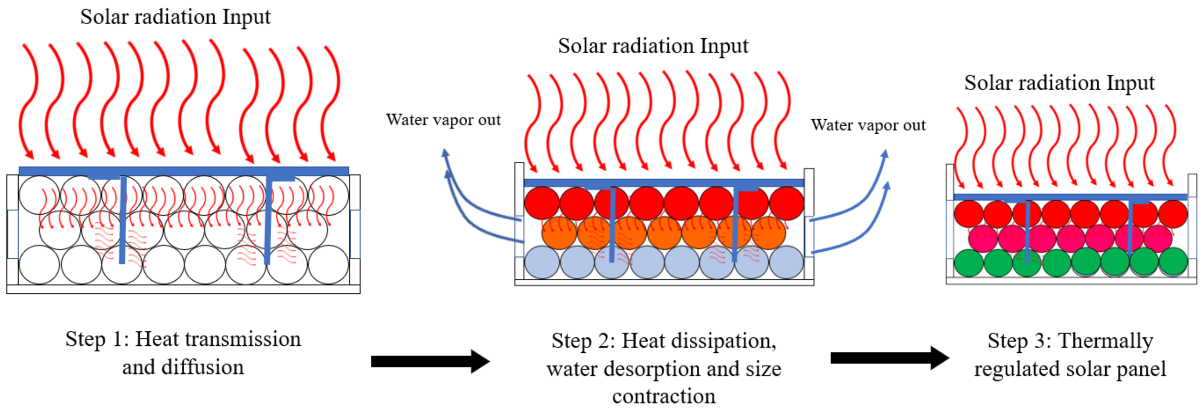

Figure 1: Thermal regulation process for the hydrogel bed cooled solar panel.

Hydrogels spheres -with initial diameter before saturation of (1-2) mm and (8-10) mm diameter after complete saturation- were tested as a cooling bed for solar panels. Four different bed configurations were tested including: 1 raw bed, 2 raw bed, 2 raw with fins and 3 raw with fins. Three different solar radiations of (600, 800 and 1000) W/m^2 were set up for the experimental purpose to simulate the minimum, average and maximum incident radiation over solar panels. Results obtained were compared for each solar radiation and the best configuration was concluded. The best bed configurations were also compared with the optimum results for Activated alumina cooling from reference [15].

2. Experimental Setup

A solar simulator was built and calibrated using 6 x 1000 W halogen lamps due to their spectrum closeness to the actual solar radiation [24]. Three aluminium plates were painted dark blue with the same optical characteristics of solar panels for the simulation purpose [25, 26]. Worth mentioning that this simulation techniques has been used by many researchers before and the results obtained showed a great similarity with the real solar panels [27, 28].

Radiation values were set to simulate the actual heat percentage supplied to the cooling system by deducting the electricity conversion percentage that represents the electrical efficiency of the panel itself from the total radiation under concern- e.g. 600, 800 or 1000 W/m^2. The heat transmitted to the cooling system -hydrogel bed- were calculated as shown in equation 1 and 2.

$$Q_{trans.} = I_{total} - E_{generated} \qquad \text{Eqn.1}$$

$$E_{gnereated} = I''_{total} * A_s * \eta_{electric} \qquad \text{Eqn.2}$$

Where:

$Q_{trans.}$: Heat transmission value need to be removed by the cooling system. (W)

I_{total} : Total incident radiation e.g. 600, 800 or 1000 W/m^2 multiplied by the panel area (W).

$E_{generated}$: Electricity generated (W)

I''_{total}:incident radiation intensity 600, 800 or 1000 W/m^2

A_s: Area m^2

$\eta_{electric}$; Estimated electrical efficiency based on operating temperature from Evans equation [27].

$$\eta_{elec.} = \eta_{T_{ref}}\left[1 - \beta_{ref}\left(T_{Panel} - T_{ref}\right)\right] \qquad \text{Eqn.3}$$

Where:

$\eta_{T_{ref}}$ is the solar panel efficiency at standard test conditions. The value for this efficiency was estimated to be 17% according to a commercial multi-crystalline solar panel from Trina -data sheets (ALLMAX- PD05.08)-.

β_{ref} is Temperature coefficient value, taken as 0.0045 C^{-1} for multi-crystalline PV panels [28],

T_{ref} is the standard test temperature which is 25 °C.

Solar radiation, ambient temperature, relative humidity and air velocity within the test area were monitored and controlled. Solar power meter was used for measuring the incident radiation over the test specimen and controlled using 2 x 3kW variable transformers to control the radiation intensity. Laboratory ventilation system was used to control the ambient temperature and the relative humidity, monitored by a digital environmental meter. The air velocity was set to zero inside the test area to avoid its effect. Figure 2 shows the complete test rig used for testing the proposed system.

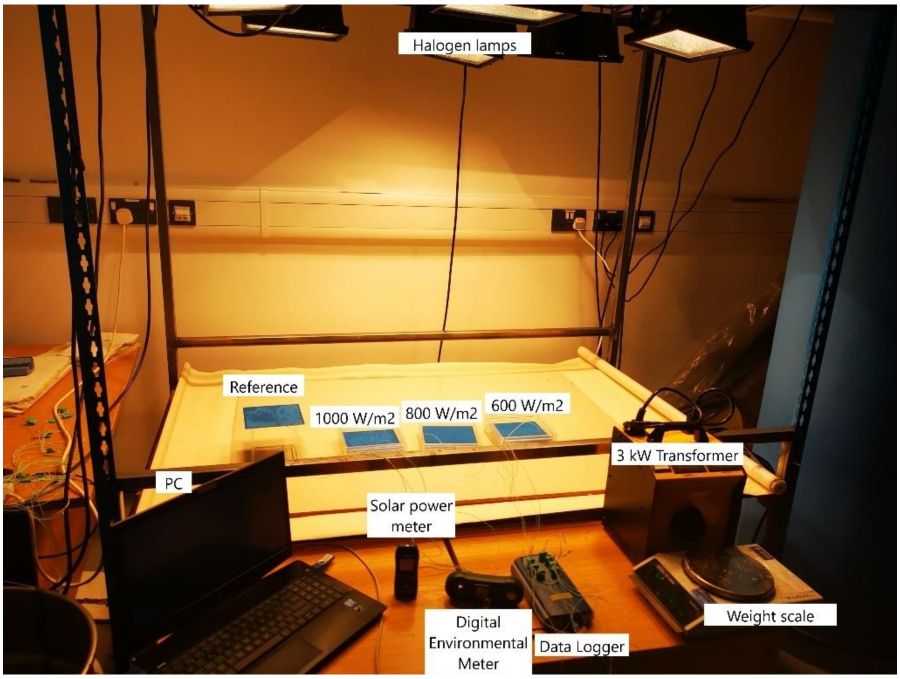

Figure 2: Experimental test rig

Four different configurations were tested to optimise the system performance. Figure 3 represents a schematic setup for all tested configurations.

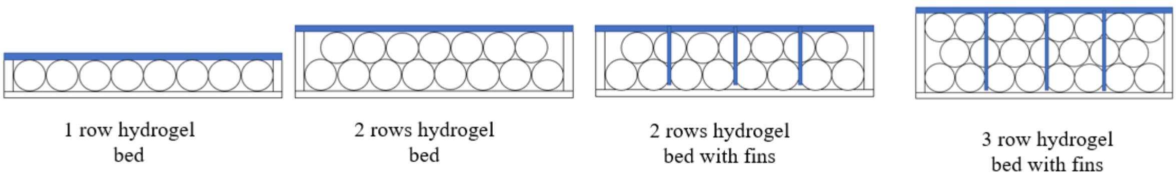

Figure 3: Schematic setup for tested configurations.

8 K-type thermocouples were attached to the back surface of the simulated plates (2 Thermocouples for each back surface) and the readings were recorded and stored on a core i7 laptop every 5 minutes Via an 8-Points data logger. All recorded temperatures were analysed and compared at different radiations and different system configurations. The system weight before adding hydrogels, after adding hydrogels and after running each experiment was measured by the high accuracy digital weight scale for determination of water content and evaporation quantities. Figure 4 shows a schematic diagram of test rig components.

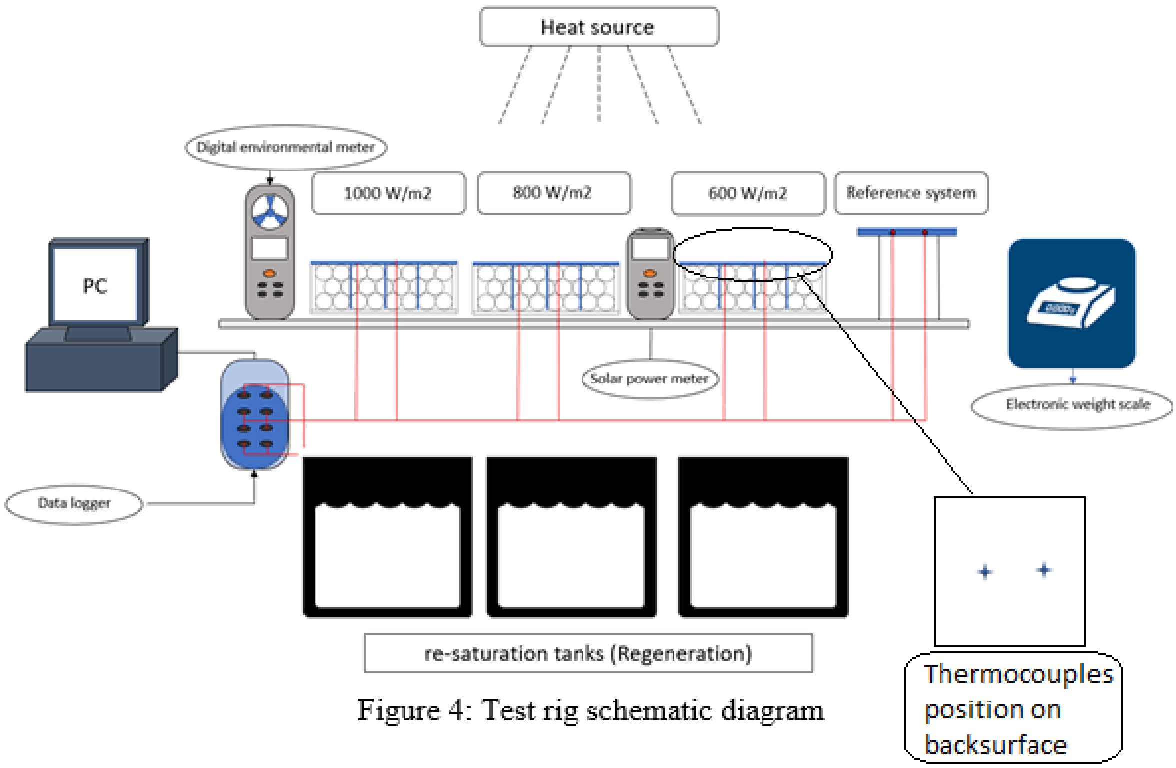

Figure 4: Test rig schematic diagram

Full specifications of used measuring devices in these experiments are given in table 1.

Table 1: Measuring devices specifications.

Thermocouples	Type	K-Type
	Range	0 to 275 °C
	Accuracy	+/- 0.5˚C
Data Acquisition system	Type	Pico Technology TC-08
	Accuracy	±0.2 %
	Range	-270 to 1370 °C
Solar power meter	Type	EXTECH SP505
	Range	0 to 3999 W/m^2
	Accuracy	±10 W/m^2
Digital environmental meter	Model	EXTECH 45170
	Velocity range – accuracy	(0.4 – 30) m/s - +/-3%
	Relative humidity range- accuracy	(10-95) % - +/-0.1%
	Temperature range	(0 – 50) ºC - +/- 1˚C
Weight scale	Range	0 to 4 kg
	Accuracy	±10 g

3. Experimental Procedures

Three similar line-perforated boxes were made to hold hydrogels sphere. Dry (1-2) mm diameter hydrogel spheres were saturated with water for 4 hours by water submersion till the final saturation volume of (8-9) mm diameter was achieved. Figure 5 shows a sample hydrogel spheres before saturation, after saturation and after experiments.

Figure 5: Hydrogel spheres before saturation, after saturation and after experiments.

The installed configurations, shown in figure 6, were tested and compared with the un-cooled system at different solar radiations.

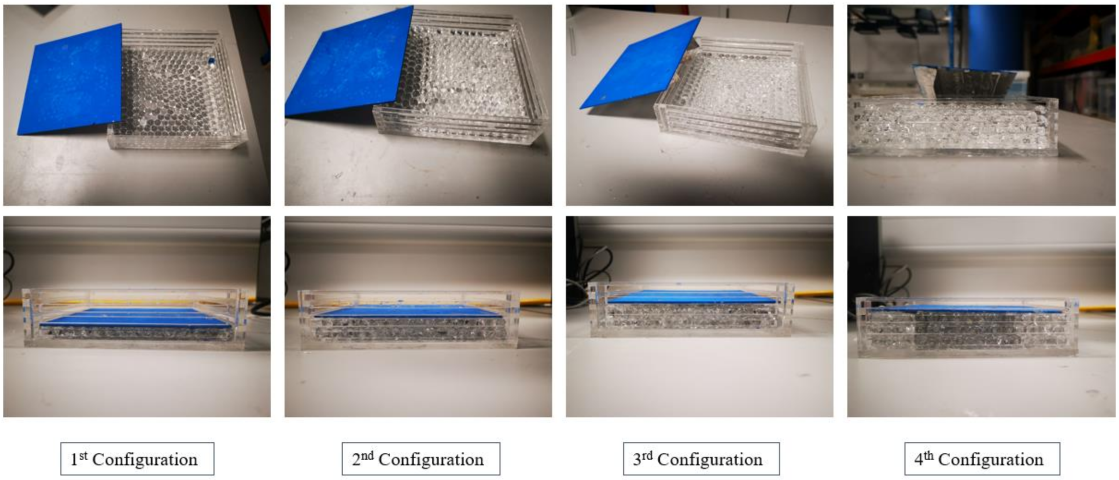

Figure 6: Different tested system configurations.

Experiments were run and repeated for 6 continuous hours under the three different mentioned radiations. Test area temperature was kept at 30 ^{o} C +/- 2^{o} C with a relative humidity range of 45-55 % and was controlled using the lab ventilation system.
Results obtained from repeated experiments were stored on the attached PC memory and inserted into an Excel file for comparison. The mean values of the repeated experiments were taken and plotted in the following results section and the mean temperature values were inserted into Evans formula (equation 3) to calculate the estimated output electrical efficiency. Finally, results obtained from these experiments were compared with the ones obtained from

Activated alumina system at different radiation intensities for different system aspects, including temperature regulation, system outputs and weight.

4. Experimental errors and uncertainties

Uncertainty analysis is one of the most important aspects to be considered when doing experimental work. This analysis depends mainly on the used instruments accuracy. Depending on the application, the acceptable uncertainty value changes. For low hazard engineering applications, this value is 5%. The less this value, the more accurate the results. Uncertainty value can be calculated using the following formula [29]:

$$e_r = \left[\left(\frac{\partial R}{\partial V_1} e_{v1}\right)^2 + \left(\frac{\partial R}{\partial V_2} e_{v2}\right)^2 + \cdots + \left(\frac{\partial R}{\partial V_n} e_{vn}\right)^2\right]^{0.5} \qquad \text{Eqn.4}$$

The uncertainty value for these experiments was calculated as +/- 0.898, which is acceptable for solar energy applications.

5. Results and Discussion

Results for the hydrogel cooling system were analysed, from both thermal perspective and estimated electricity output, and compared with the standard un-cooled solar panels.

5.1. Hydrogel system's temperature and efficiency

Figures 7.a, 7.b and 7.c show the back-surface temperature at 600, 800, and 1000 W/m^2 radiation intensities respectively.

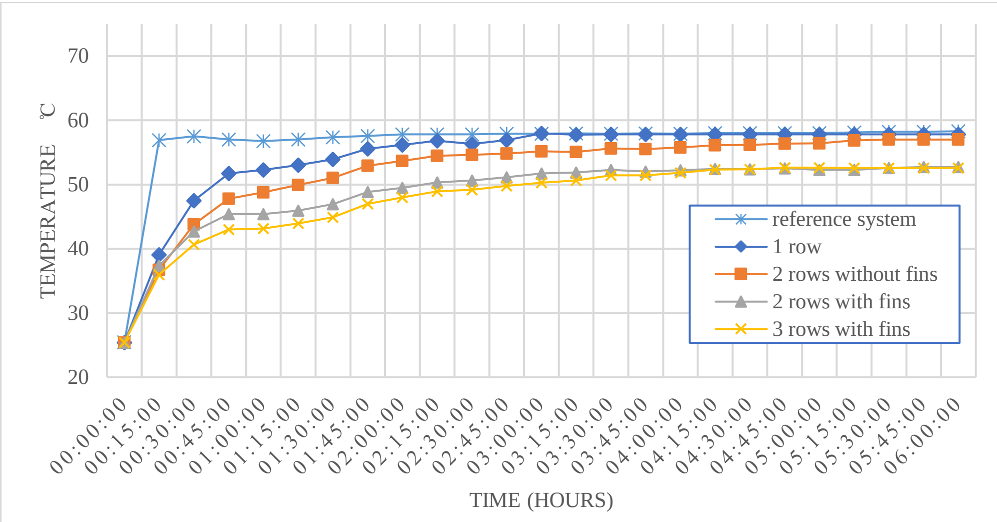

Figure 7.a

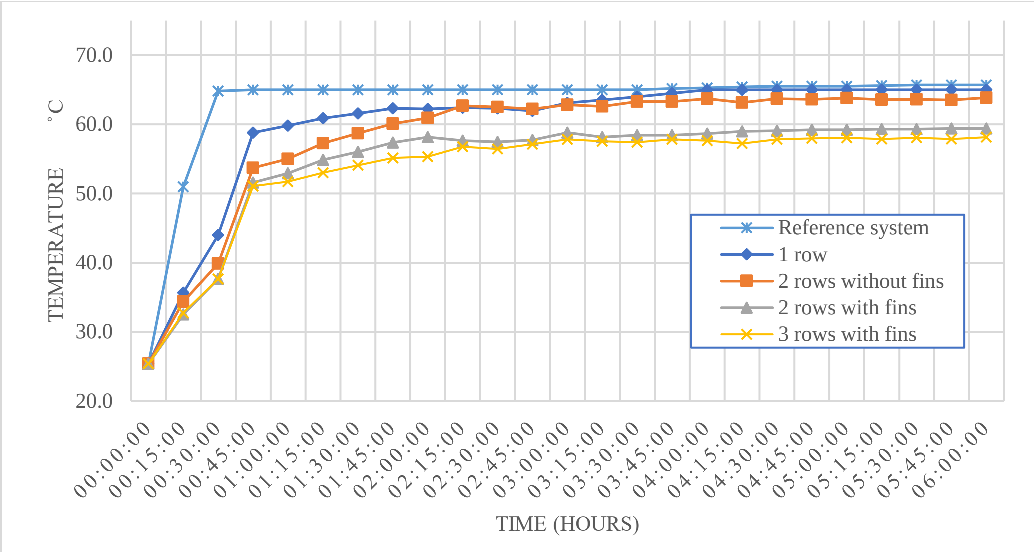

Figure 7.b

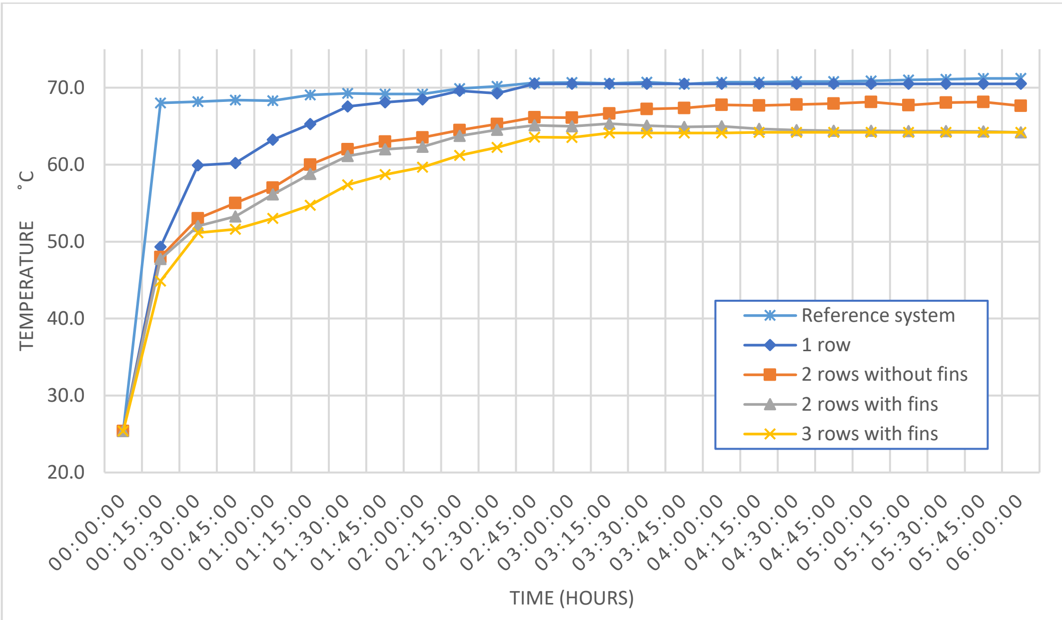

Figure 7.C

Figure 7: Back surface temperature change with time at different radiation intensities

a) 600 W/m^2 b) 800 W/m^2 c) 1000 W/m^2

From the above figures, it is clear that adding hydrogels bed under the simulated solar panels, even with different configurations, reduced their temperatures for all radiation intensities used. The stand-alone (reference system) recorded the highest temperature followed by the one row bed, 2 rows bed without fins, 2 rows bed with fins and the 3 rows with fins comes with the best cooling performance and the lowest recorded temperature.

The one row bed without fins proved to give a reasonably good cooling performance for almost 3 hours which is cooler than the reference panel; however, after this time, there is no cooling effect visible. This lack of cooling effect occurred because most of the water/water content inside the hydrogel bed has evaporated within the first three hours. The two rows bed without fins showed an enhanced effect compared to the one row bed as it kept the cooled system temperature below the reference system for the whole experimental period. Due to the fact that

2 rows system has a larger water content, it is able to absorb the heat from the back surface and evaporate, while leaving the cooled system at a lower temperature.

In order to enhance the heat transmission through the different layers of the hydrogels, 3 Aluminium fins were attached to the back surface. From figures 7, it is obvious that adding fins enhanced the heat transfer through the bed depth and allowed more heat to be dissipated. Using three layers instead of two with fins showed a better performance, especially for the first four hours of the experiment, due to achieving the steady state temperature of the system and the reduction in the heat removal capacity for the cooling bed. Average temperature reduction over the test period of 9, 9.6 and 10 ˚C was achieved at 600, 800 and 1000 W/m^2, respectively.

The obtained temperature reduction was echoed as an increase in the estimated electrical performance calculated using Evans equation for electrical efficiency. Figure 8 below shows graphs of estimated electrical efficiency for different systems configuration versus the un-cooled panel at radiations intensities of 600, 800, and 1000 W/m^2.

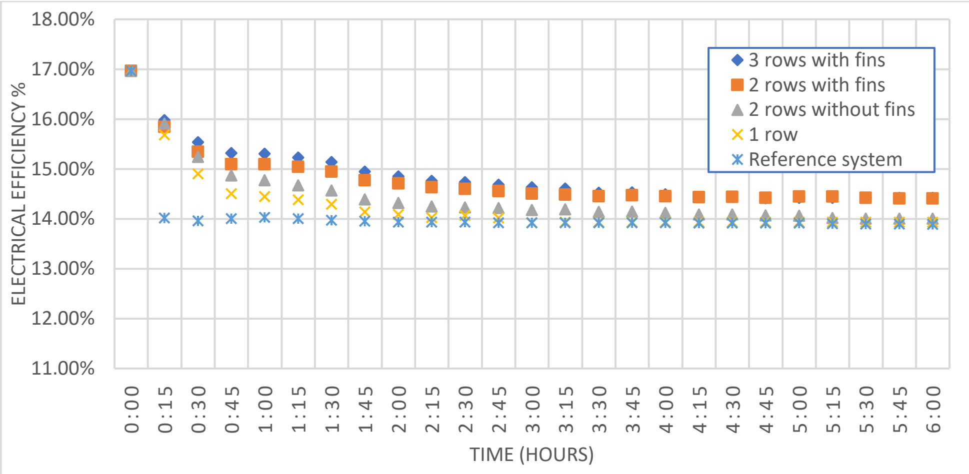

Figure 8.a

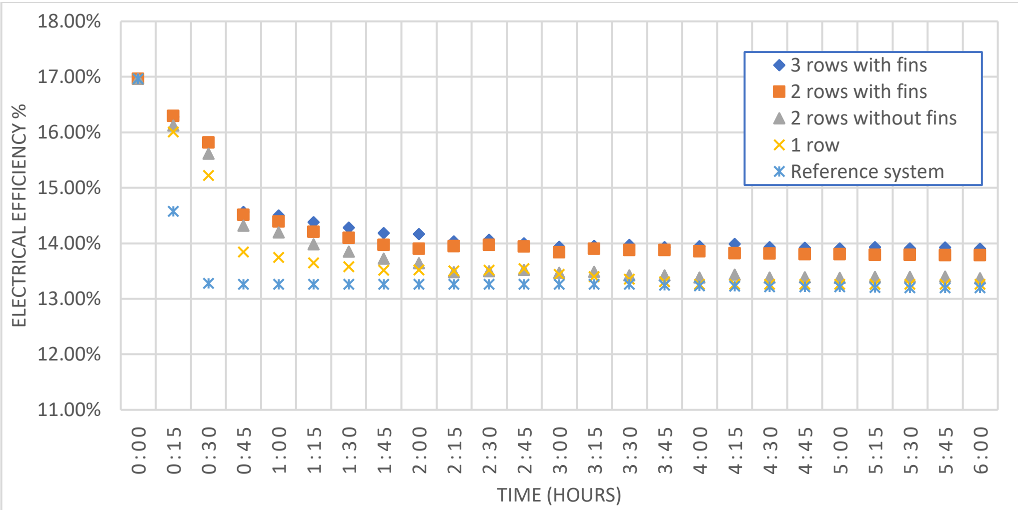

Figure 8.b

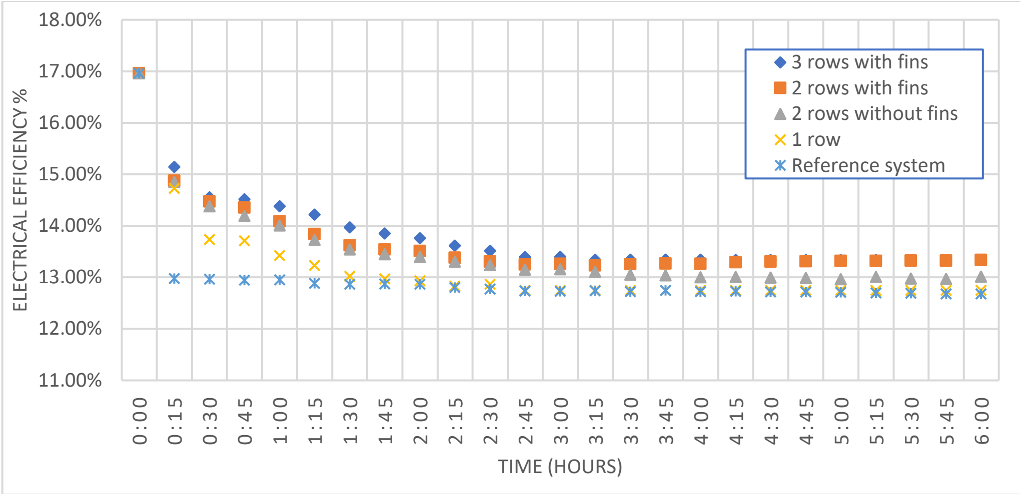

Figure 8.c

Figure 8: Estimated electrical efficiency change with time at different radiation intensities
a) 600 W/m^2 b) 800 W/m^2 c) 1000 W/m^2

From above figures, it is clear that the proposed cooling technique using hydrogel can effectively increase the electrical efficiency of solar panels. From the data analysis, the enhancement in energy generation recorded values of 6.2 %, 6.3% and 6.5% at solar radiation intensities of 600, 800 and 1000 W/m^2, respectively were obtained.

Table 2 represents a summary of results at different radiation intensities. The average reduction in temperature was determined using equation 5 below

$$\Delta T_{avg} = \frac{\sum_1^n (T_{ref.} - T_c)}{N} \qquad \text{Eqn.5}$$

Where:

T_{ref}: Un-cooled system temperature °C

T_c : proposed system temperature °C

N: Number of readings

Efficiency enhancement was also calculated as follow

$$\Delta\%_{increase} = \frac{\eta_{c.} - \eta_{ref}}{\eta_{ref}} \ \% \qquad \text{Eqn.6}$$

Where:

η_{ref}: The uncooled system efficiency %

η_c : cooled/proposed system efficiency %

And the average enhancement was determined using equation 7.

$$\Delta\%_{avg} = \frac{\sum_1^n \Delta\%_{increase}}{N} \qquad \text{Eqn.7}$$

Table2: Results summary at different radiations using different systems configurations.

Solar Radiation W/m^2	System Configuration	Average Temperature Reduction ($\pm\mathbf{0.5^\circ}$ **C**)	Average Efficiency Improvement % (($\pm\mathbf{0.15}$%)
600	1 row bed	2.3˚C	1.53%

	2 rows without fins	4.5˚C	3%
	2 rows with fins	8˚C	5.4%
	3 rows with fins	9˚C	6%
800	1 row bed	3.1˚C	2.3%
	2 rows without fins	5.0˚C	3.5%
	2 rows with fins	8.2˚C	6.1%
	3 rows with fins	9.5˚C	7%
1000	1 row bed	3.3˚C	2.3%
	2 rows without fins	6˚C	4%
	2 rows with fins	8.5˚C	6.2%
	3 rows with fins	9.6˚C	7.2%

5.2. Comparison between the activated alumina and hydrogel system

In order to compare between hydrogel and activated alumina [14], selected results from both experiments were plotted versus each other and compared with the uncooled system. Figures 9.a, 9.b, and 9.c represent temperature variation versus time at the low, medium and high intensities respectively.

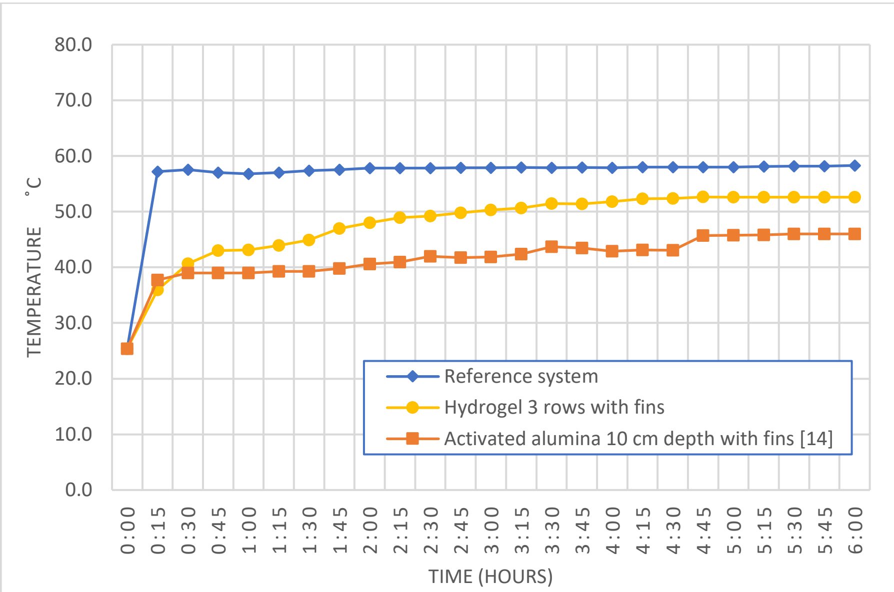

Figure 9.a

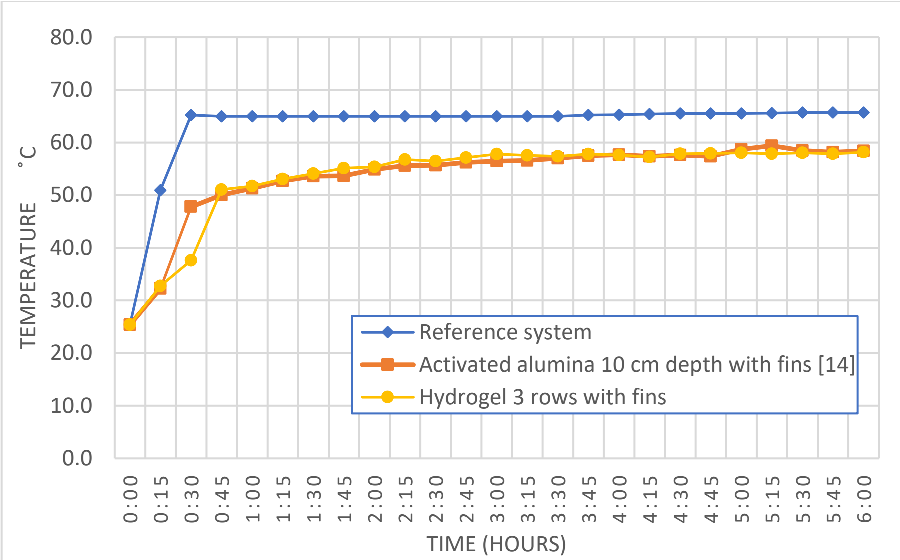

Figure 9.b

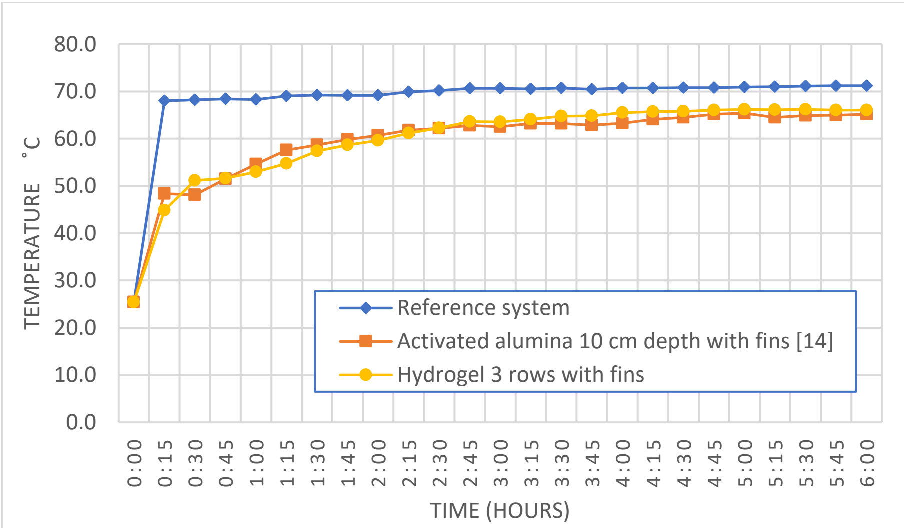

Figure 9.c

Figure 9: Comparison between activated alumina and hydrogels as a cooling-agents at different radiation intensities.

a) 600 W/m^2 b) 800 W/m^2 c) 1000 W/m^2

From figure 9, it is obvious that activated alumina and hydrogels gave the same cooling performance at different radiations intensities of 800 and 1000 W/m^2 over time. However, at the lowest radiation, the activated alumina system proved to give a better performance due to its ability to diffuse the water at low radiations as the heating process take longer time to happen and larger exposed surface area that increased the convection effect.

Table 3 presents a comparison between the best results obtained from the hydrogels from this research and the activated alumina reported results from literature (reference [14])

Table 3: Comparison between activated alumina and hydrogels system.

Comparison parameter	Hydrogel	Activated alumina [14]
Temperature reduction at 600 W/m^2	9℃	14.9℃
Temperature reduction at 800 W/m^2	9.5℃	9.5℃
Temperature reduction at 1000 W/m^2	9.6℃	8.9℃

Efficiency improvement at 600 W/m^2	6 %	9.93%
Efficiency improvement at 800 W/m^2	7 %	6.7%
Efficiency improvement at 1000 W/m^2	7.2 %	6.5%
Weight increase per m^2 panel	26.6 kg	85.6 kg
Heat storage / extraction	No	Yes

From the table above, it can be seen that hydrogels can be used effectively as a cooling agent for solar panels and are fairly comparable with the activated alumina. Moreover, hydrogel system has also the advantage of less weight per meter square compared with activated alumina system; however, the heat storage in the activated alumina system can be recovered by different means which is not the case for the hydrogels. Using hydrogels in such systems can lead to different economic advance opportunities. First of all, will increase the output power from solar panels using the same surface area of the panel. Reducing the panel temperature can lead for further increment in panel's lifetime, reduction in efficiency degradation with time. Compared with activated alumina, it is much lighter system than the activated alumina one, which give it the advance of installation easiness and lower installation cost.

For hydrogels re-saturation process, submersion tank is required for 2-3 hours submersion process for full volume growth. Hydrogels proved with experiments to be fully reusable but full water desorption (complete drying process) doesn't support full volume recovery after all. So, it is recommended not to allow hydrogels to be completely dry during the heating process. Further research opportunities are to consider varying metrological conditions including, wind speed, ambient temperature, relative humidity and performing outdoor studies are promising points as a future work. Testing the system under different tilting angles and orientation is also a point to discuss in future research. Saturating the hydrogels with super conductive additives or saltwater can be more economic and more effective however, further investigation on material properties needs to be discussed. Also considering hydrogels on the top surface can lead to further temperature reduction however, the absorbed light fraction by the hydrogel spheres needs to be considered.

6. Conclusions

Hydrogel beds with different configurations were tested as a stationary/passive back surface coolant for solar panels. Beds were formed with hydrogel spheres arranged as layers/rows. Four configurations were tested and compared with the un-cooled system. The tested four configurations were 1 row bed, 2 rows bed, 2 rows bed with fins and 3 row bed with fins. Three radiations were used during experiments to represent the highest (1000 W/m^2), mean (800 W/m^2) and lowest 600 W/m^2 radiation.

Results showed that hydrogel bed effectively reduced the temperature of the panel at different radiation intensities. 3 rows bed with fins showed the best thermal performance. A temperature reduction range between 9 and 9.6 ˚C was achieved at radiation intensities of 600 and 1000 W/m^2, respectively. The estimated efficiency increased by 7.2% at 1000 W/m^2 using the 3 rows bed with fins.

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