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1 author:

Abdulhameed Mambo
Nile University of Nigeria

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Investigating the Potential of Wind as a Recovery Improvement of Building Integrated Photovoltaic's Tiled Roof Using Indoor Solar Simulator

*A.D. Mambo, S. Zubair, H.T. Abdulazeez, and S. Ahmad

Building Energy Research Group, Department of Civil and Building Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, United Kingdom

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A B S T R A C T

Photovoltaic (PV) cells when integrated within a building façade, offers the possibility of generating power and heating/cooling onsite. However, PV will exhibit long-term degradation if the temperature exceeds a certain limit. In order to improve PV power and system efficiency and avoid structural deformities, it is necessary to keep PV cell temperature and cell reflection as low as possible. This study investigates the effects of wind flow on thermal and electrical performances of PV roof tiles using large scale indoor solar simulator. The study found that electrical performance improves from about 9 - 9.3% while thermal performance improves greatly from about 68 - 83% and it took only 1/5th of the time for the attainment of steady state temperatures when the 'without wind flow' was compared 'with wind flow' performance. Considering all experimental sources of error, the performance values attained agrees with the range of efficiency values reported in text books for photovoltaic roof tiles. Therefore, wind flow improves the thermal and electrical efficiency of PV roof tiles and could serve as a recovery improvement.

1. Introduction

Africa south of the Sahara, a region in dire need of energy, lies within the high sunshine belt and has a great potential in solar and wind energy. A study [1] reported an average monthly solar irradiance of between 3.50-5.43 kWh/m^2 and 5.62-7.01 kWh/m^2 for south and north of Nigeria respectively. This high solar insulation presents a huge opportunity in these areas for onsite thermal and electrical power generation to meet the ever growing energy demand but operational efficiency of PV systems exposed to very high solar insulation have been a source of great concern.

There are significant research activities attempting to improve the operational efficiency of photovoltaic cells [2]. The same solar simulator facility used in this study to was also used to investigate the potential for high temperature operation of building integrated PV

• Corresponding author.
email address: a.d.mambo@lboro.ac.uk

roof tiles [3]. They conclude that for the particular roof tile investigated, there is a warrantee in operational temperatures of up to 85^{0}C beyond this the integrity of encapsulation could be compromise. An assessment of experimental data was presented for electrical and thermal performance evaluation of photovoltaic (PV) systems integrated as cladding components into the building envelope, giving input to modelling and analysis work [4]. John & Brett, (2006) presented the result of tests conducted and the practical and scientific implications of using a transpired solar collector with conventional PV to create a solar co-generation system [5]. Abdolzadeh & Ameri (2009) investigated the effectiveness of spraying water over the front of PV cells. The results showed that PV cell power is increased significantly due to this treatment [6].

This study investigates the potential of wind as a recovery improvement of thermal and electrical efficiency of a building integrated PV roof tile.

2. Materials and Method

The test was conducted using a large scale indoor solar heating simulator (a source producing radiant energy that has spectral distribution, intensity, uniformity in intensity and direction closely resembling that of the solar radiation) in the Department Civil & Building Engineering laboratory, Loughborough University, United Kingdom. The experiment set-up comprises of a section of conventional roofing tiles tilted at an angle of 40 degrees to the horizontal, the upper surface of which was clad with a layer of PV material. Radiant heating of the test material was provided by 8 Sol 1200 lamps placed directly overhead the roof tile by metal frame to simulate solar spectrum. These lamps are capable of producing a natural sunlight spectrum to D65 standard with an air mass ratio of 1.5, and can deliver irradiance incident on the test surface of up to 1000 W/m^2 with a uniformity to within ±10% [3]. This test was conducted at a cell temperature of about 25^{o}C and a nominal irradiace 800 W/m^2 to meet the test conditions for performance at STC (Standard Test Conditions) and NOCT (Norminal Operating Cell Conditions) as stipulated in IEC 61646 : 2008. The laboratory's temperature represents the 'outdoor' conditions was provided by an air conditioner. The front face of the test element was ventilated by three standing fans to simulate wind conditions.

Temperature sensors were used to measure the temperatures at the inlet and outlet of the roof tile and of each 7 PV laminates *(see table 3 below). (Refer to figure 1 and 2 for the schematics and pictures of the experiment set-up).*

Procedure

The equipments were set-up as discribed above. The PV dimensions strips were measured. Dimensions of the air vent attached to the front of the simulator were also measured. The internal fans of the simulator were turned on and the velocity of air flow coming out of the air vent was measured and average velocity of air flow was thus determined. This value was used to calculate the mass flow rate of air from equation *1*. The positions of temperature and the irradiance sensors were noted.

$$\dot{m} = A_v \times V \times \rho_{air} \quad (1)$$

Where :

A_v = Area of vent [m^2]

V = Mean air velocity [m/s]

ρ_{air} = Density of air [kg/m^3]

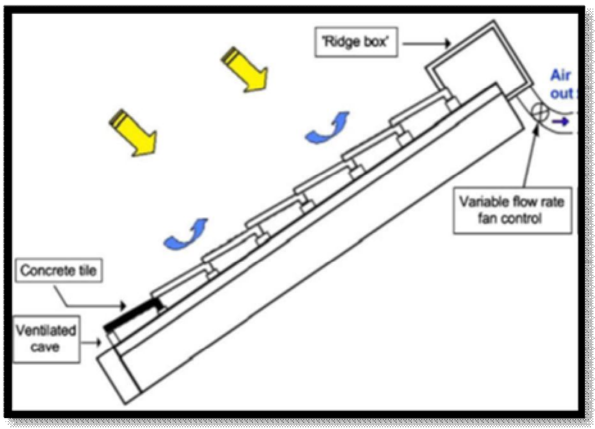

Figure 1. Schematics drawing of PV roof tile test element [3]

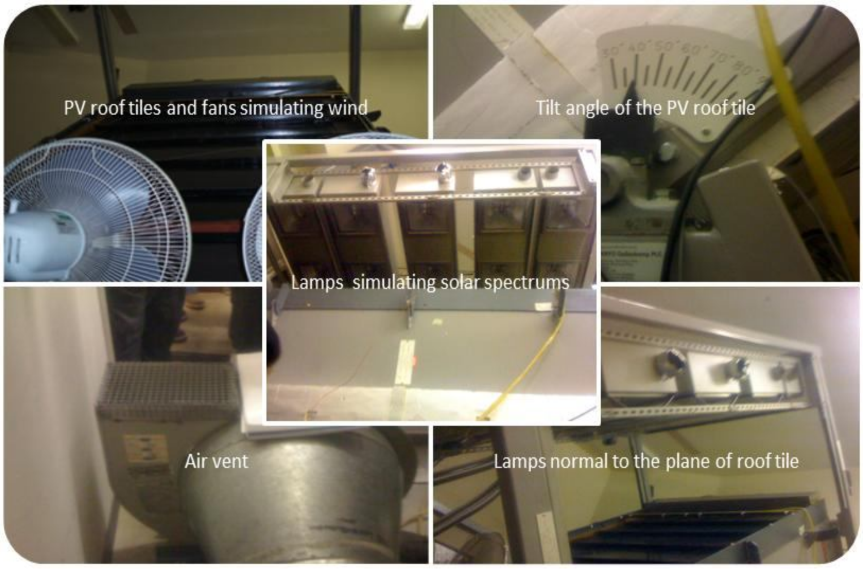

Figure 1. Experiment set-up in pictures

Without Wind Condition

From the control room and with the lab room door closed and secured, the lamps were let on. The standing fans were however off at this stage to impose a 'without wind' condition. The air temperature inside the roof tile was monitored at one minute interval and plotted on a graph of temperature against time until a steady state condition was observed *(see table 2 and figure 3 for summary of results*). The time constant, the time required for a fluid leaving a collector to change through 0.632 of the total change from its initial to the ultimate steady state values after a step change in inlet fluid temperature, was estimated from the plot *(see figure 3)*. The PV electrical power output was noted, the inlet and the outlet temperatures were also obtained.

From the values obtained, the electrical and thermal efficiencies of the PV were calculated using equation 2 and 3.

Where :

$$\eta_{electrical} = \frac{P}{G \times A_{pv}} \qquad (2)$$

$$\eta_{thermal} = \frac{Q}{G \times A_{pv}} \qquad (3)$$

η = Rated efficiency

A_{pv} = Area of PV module or array [m^2]

G = absorbed solar irradiance at standard testing condition [W/m^2]

Q = heat transfer flux [W]

P = Electrical power output [W]

Here, rated efficiency is defined as the ration of energy obtained the from the PV module to the solar energy absorbed by the module. Solar energy is proportional to the product of absorbed solar irradiance and the surface area of the PV module or array.

With wind condition

After the attainment of the 'without wind' steady state, the fans were remotely switched on to simulate external wind condition and the PV air temperature monitored at 1 minutes interval and values of temperature against time were plotted untill steady state temperatures was observed. Time constant was estimated and efficiencies calculated as above *(see table 2 and figure 4 for summary of results).*

Sources of error

1. Accuracy of any experiment depends on the quality of equipment, the expertise of the operator and the intent of measurement [7], although the first condition was met and the last understood, and we were

briefed by experts, we were no 'expert' operators.

2. The assumption of steady state operation of an indoor solar collector requires constant rate of air flow, uniform solar radiation and uniform wind, this is different from vagaries of real life situation [8].

Precautions

1. Air velocities and other linear dimensions were measured by taken readings directly at eye level to avoid parallax error.
2. 60 air velocity readings were taken from the air vent and averaged so as to obtain a more representative value of the mean air velocity *(see table 1 below).*
3. Three numbers of volunteers were recruited to handle the various segments of the experiment which includes; monitoring temperature perturbation, time keeping, plotting on graph sheets to produce better quality in data collection and collation.
4. The simulation room was evacuated, the door closed and secured before the solar lamps were remotely switched on to protect people from exposure to harmful UV radiations from the lamps.
5. The results were reported with their margin of uncertainties.

3. Results

Lab room temperature = 25 ± 0.2 ^oC

PV Roof tile Outlet air temperature = 38 ± 0.2 ^oC
PV Roof tile Inlet air temperature = 27.9 ± 0.2 ^oC
Measured electrical power output = 149 + 5W
The Area of the air vent test duct, A_v = 0.040 m^2
Air flow mean velocity, V = 3.48 m/s (see table 1)
Mass flow rate of air m = 0.17 kg/s

Where ρ_{air} at 20 ^oC and 101,35
pa = 1.2041 kg/m^3
Calculation of Uncertainties in mass flow rate is shown in equation *4* and *5*.

$$\Delta A = A\left[\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta W}{W}\right)^2\right]^{0.5} = \pm 0.0003\,m \quad (4)$$

$$\Delta \dot{m} = \dot{m}\left[\left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta V}{V}\right)^2\right]^{0.5} = \pm 0.0051\,\frac{kg}{s} \quad (5)$$

Therefore $\dot{m} = 0.17 \pm 0.0051$ kg/s

Table 1. Values of velocity (m/s) measured in each grid of the air duct outlet

Velocities from each of the 60 perforations on the air vent									
1.5	3.0	2.8	1.3	1.5	2.8	4.0	6.5	7.5	8.0
1.3	2.5	2.0	1.3	1.5	2.3	5.0	6.0	8.0	8.5
3.0	2.0	1.0	1.0	1.0	1.8	4.8	6.5	8.0	7.5
2.0	1.5	1.2	1.0	1.0	1.8	3.0	6.0	7.5	7.0
2.0	2.5	1.4	1.2	1.5	2.0	5.0	7.5	8.0	9.0
1.0	2.0	0.9	0.7	1.0	1.5	2.5	3.5	5.5	4.0
$sum = 208.4\ (m/s)$			*Mean velocity*			208.4/60 = 3.48 (m/s)			

Table 2. Temperature (^{o}C) versus time (minutes) 'with (out) wind' scenario

WITHOUT WIND								WITH WIND			
Time (Minutes)	**Temp (^{0}C)**	**Time (Minutes)**	**Temp (^{0}C)**	**Time (Minutes)**	**Temp (^{0}C)**	**Time (Minutes)**	**Temp (^{0}C)**	**Time (Minutes)**	**Temp (^{0}C)**	**Time (Minutes)**	**Temp (^{0}C)**
0	*20.2*	11	*46.4*	22	*56.5*	33	*57.1*	0	*58.8*	12	*50.4*
1	*20.4*	12	*47.9*	23	*56.7*	34	*57.1*	1	*57.5*	13	*50.2*
2	*23.8*	13	*49.3*	24	*56.8*	35	*57.3*	2	*55.0*	14	*50.0*
3	*27.5*	14	*50.3*	25	*56.9*	36	*57.5*	3	*55.0*	15	*49.7*
4	*30.5*	15	*51.4*	26	*56.9*	37	*57.8*	4	*54.0*	16	*49.5*
5	*33.4*	16	*52.6*	27	*56.9*	38	*57.8*	5	*53.2*	17	*49.5*
6	*36.1*	17	*53.5*	28	*56.9*	39	*58.0*	6	*52.6*	18	*49.3*
7	*38.7*	18	*54.4*	29	*57.0*	40	*58.2*	7	*52.1*	19	*49.2*
8	*40.9*	19	*55.2*	30	*57.0*	41	*58.4*	8	*51.6*	20	*49.1*
9	*42.9*	20	*55.9*	31	*57.4*	42	*58.7*	9	*51.3*	21	*49.0*
10	*44.8*	21	*56.3*	32	*57.3*	43	*58.8*	10	*50.8*	22	*48.8*
								11	*50.6*	23	*48.7*

Table 3. Temperature in each PV panel

PV tiles No	**PV1**	**PV2**	**PV3**	**PV4**	**PV5**	**PV6**	**PV7**
PV tiles Temp Without Wind (^{o}C)	52.9	55.2	58.0	58.8	59.0	58.3	58.8
PV tiles temp with wind (^{o}C)	41.5	43.63	46.81	48.47	50.94	53.25	51.33

Without fan/wind

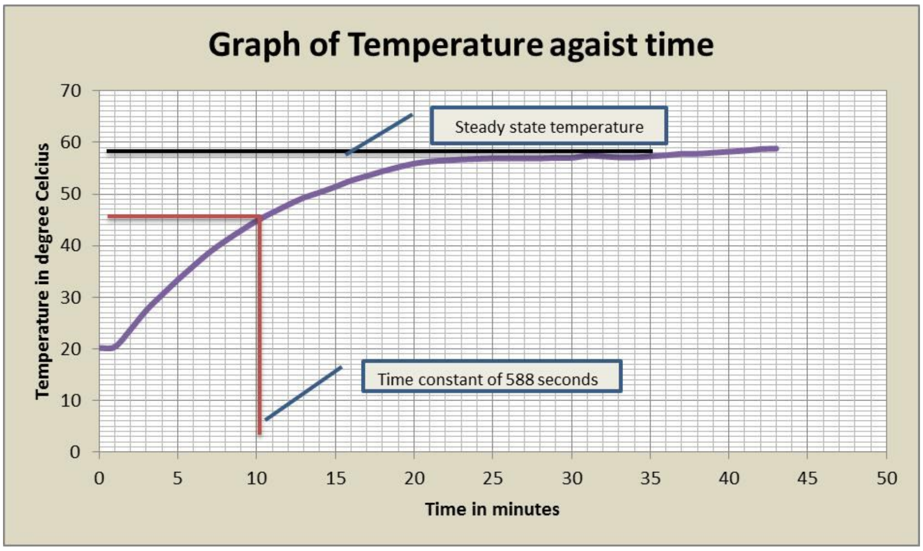

Figure 3. A graph of temperature against time for the without wind test

From the graph in *figure 3*, the steady state temperature is 58^{o}C and since the initial temperature is 20.2^{o}C, the total change from the initial to the steady state temperature is 37.8^{o}C the time constant; a time corresponding to 0.632 of the total change after a step change in inlet fluid temperature of the for the without wind experiment is 9.8 minutes.

Electrical efficiency

$$\eta_{elec} = \frac{P}{G \times A_{pv}} = \frac{140}{(800 \times 5 \times 0.32 \times 1.180)} = 0.092 = 9.2\%$$

Uncertainty in electrical efficiency

$$\Delta A_{pv} = A_{pv}\left[\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta W}{W}\right)^2\right]^{0.5} = \pm 0.001\, m^2$$

$$\Delta P = \pm 5\, W, \Delta I = \pm 50\, W/m^2 \text{ and } \Delta A = \pm\, 0.001\, m^2$$

$$\Delta\eta_{elec} = \eta_{elec}\left[\left(\frac{\Delta P}{P}\right)^2 + \left(\frac{\Delta I}{I}\right)^2 + \left(\frac{\Delta A}{A}\right)^2\right]^{0.5} = \pm 0.01$$

$$\text{Therefore } \eta_{elec} = 9.2 \pm 1\%$$

Thermal efficiency

$$\eta_{therm} = \frac{\dot{m} \times C_p \times (t_o - t_i)}{G \times A} = 0.679$$

Uncertainty in thermal efficiency

$$\Delta(t_o - t_i) = [(\Delta t_o)^2 + (\Delta t_i)^2]^{0.5} = \pm 0.283\ ^\circ\mathrm{C}$$

$$\Delta A_{roof} = A_{roof}\left[\left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta W}{W}\right)^2\right]^{0.5} = \pm 0.0027\, m^2$$

$$\text{Also } \Delta\dot{m} = \pm 0.0051\, kg/s \text{ and } \Delta I = \pm 50\, W/m^2$$

$$\Delta\eta_{therm} = \eta_{therm}\left[\left(\frac{\Delta\dot{m}}{\dot{m}}\right)^2 + \left(\frac{\Delta(t_o - t_i)}{(t_o - t_i)}\right)^2 + \left(\frac{\Delta I}{I}\right)^2 + \left(\frac{\Delta A}{A}\right)^2\right]^{0.5} = \mp 0.05$$

$$\text{Therefore, thermal efficiency } \eta_{therm} = 0.679 \pm 0.05 = 67.9 \pm 5\%$$

With fan/wind

Lab room temperature $= 25.2 \pm 0.2\ ^\circ\mathrm{C}$
PV roof tiles outlet air temperature $= 37.86 \pm 0.2\ ^\circ\mathrm{C}$
PV roof tiles Inlet air temperature $= 24.58 \pm 0.2\ ^\circ\mathrm{C}$
Measured electrical power output $= 145 \mp 5\, W$

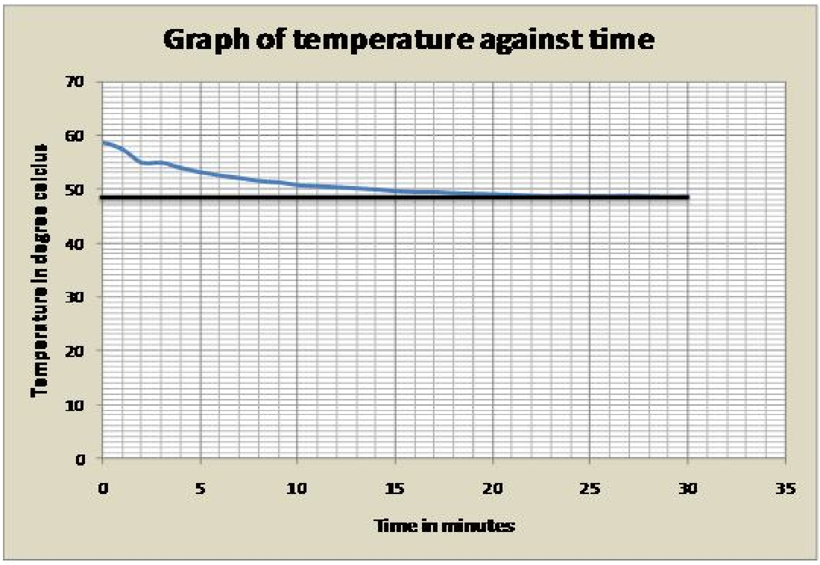

Figure 4. Graph of temperature against time of the with wind experiment

The time constant of the 'with wind' experiment is 120 seconds as shown in *figure 4* above.

Electrical efficiency

$$\eta_{elec} = \frac{P}{G \times A} = \frac{145}{(800 \times 5 \times 0.32 \times 1.180)} = 0.096$$

Uncertainty in electrical efficiency

$$\Delta P = \pm 5\ W, \Delta I = \pm 50\ W/m^2 \ and\ \Delta A = \pm 0.0012\ m^2$$

$$\Delta\eta_{elec} = \eta_{elec}\left[\left(\frac{\Delta P}{P}\right)^2 + \left(\frac{\Delta I}{I}\right)^2 + \left(\frac{\Delta A}{A}\right)^2\right]^{0.5}$$

$$= 0.0927\left[\left(\frac{5}{145}\right)^2 + \left(\frac{50}{800}\right)^2 + \left(\frac{0.001}{0.378}\right)^2\right]^{0.5} = \pm 0.0066$$

Therefore electrical efficiency $\eta_{elec} = 0.0927 \pm 0.0067 = 9.6 \pm 0.7\%$

Thermal efficiency:

$$\eta_{thermal} = \frac{0.17 \times 1012\ (37.86 - 24.58)}{(800 \times 2.3 \times 1.5)} = 0.828$$

Uncertainty in thermal efficiency

Also $\Delta(t_o - t_i) = \pm 0.283\ ^\circ C$, $\Delta A_{roof} = \pm 0.0027\ m^2$,

$$\Delta\dot{m} = \pm 0.0051\ kg/s\ \ and\ \Delta I = \pm 50\ W/m^2$$

$$\Delta\eta_{therm} = \eta_{therm}\left[\left(\frac{\Delta\dot{m}}{\dot{m}}\right)^2 + \left(\frac{\Delta(t_o - t_i)}{(t_o - t_i)}\right)^2 + \left(\frac{\Delta I}{I}\right)^2 + \left(\frac{\Delta A}{A}\right)^2\right]^{0.5}$$

$$= 0.828\left[\left(\frac{0.0051}{0.17}\right)^2 + \left(\frac{0.283}{13.28}\right)^2 + \left(\frac{50}{800}\right)^2 + \left(\frac{0.0027}{3.45}\right)^2\right]^{0.5} = \pm 0.06$$

Therefore, thermal efficiency $\eta_{therm} = 0.828 \pm 0.06$

4. Discussion of Results

The photovoltaic cell efficiency decreases with increasing temperature. Also, efficiency and electrical yield decrease with increased operating temperatures, it is preferable to keep cells temperature as low as possible. Due to the use of fan for additional cooling by evaporation, the cells operating temperatures were significantly reduced in comparison with a module without wind experiment which was measured simultaneously. This result is demonstrated by the time for the attainment of steady states as shown in *figure 3 and 4*. The time constant of the 'without wind' 588 seconds is greater than that for the 'with wind' conditions 120 seconds. Meaning that the wind enables the PV to attain 63 % of its steady state temperature at a rate 5 times faster than the without wind condition.

The test shows that lowering the PV temperature by the induced wind flow increases the thermal and electrical performance of the PV roof tiles. The test result confirms that thermal efficiency of the roof tile is much higher than electrical efficiency for the 2 cases investigated. The reported experimental thermal and electrical efficiency of between 9 - 10% and 68 – 83% for electrical and thermal efficiencies respectively is in agreement with text book values of 10-15 % and 70-95 % respectively within the limit of experimental error. This is a validation of the test procedure.

The shortcomings however is that the difference between measuring in controlled indoor conditions over realistic outdoor conditions is that the radiative heat exchange is different due to the different temperature of the surroundings and the 'sky'. That is the sky temperature will be different from the glass temperature due to lamps.

5. Conclussions

The experiment to investigate the effect of wind on electrical and thermal efficiency of a PV tiled roof was carried out using an indoor thermal simulator. The test was conducted under STC and NOCT Conditions as stipulated in IEC 61646: 2008. The test results was validated by comparing with reported text book values. It was found that wind allows the PV module to attain its steady state value 5 times faster than the without wind scenerio. Therefore wind flow improves the thermal and electrical performances of tiled roof clad with PV cells and could be used as a recovery improvement for building integrated PV tiled roof. Further works will need to be carried out to compare performances in the real outside condition.

Acknowledgements

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