The performance of a novel flat heat pipe based thermal and PV/T solar collector that can be used as an energy-active building envelope material

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ABSTRACT

A novel flat heat pipe design has been developed and utilised as a building envelope and thermal solar collector with and without (PV) bonded directly to its surface. The design of the new solar collector has been validated through full scale testing in Cardiff, UK where solar/thermal, uncooled PV and PV/T tests were carried out on three identical systems, simultaneously. The tests showed a solar/thermal energy conversion efficiency of around 64% for the collector with no PV and 50% for the system with the PV layer on it. The effect of cooling on the solar/electrical energy conversion efficiency was also investigated and an efficiency increase of about 15% was recorded for the cooled PV system due to the provided homogenous cooling. The new flat heat pipe solar collector is given the name "heat mat" and, in addition to being an efficient solar collector type, it is also designed to convert a building envelope materials to become energy-active. A full size roof that utilise this new building envelope material is reported in this paper to demonstrate the way this new collector is integrated as a building envelope material to form a roof. A thermal absorption test, in a controlled environment, from the ambient to the heat mat with no solar radiation is also reported. The test has proved the heat mat as an efficient thermal absorber from the ambient to the intermediate fluid that deliver the heat energy to the heat pump system.

Keywords

Flat heat pipe, heat mat, PV/T

Nomenclature

G	solar irradiation (W/m^2 or kWh/m^2)
Q	heat flux (W/m^2 or kWh/m^2)
I	current (A)
U	voltage (V)
A	surface area (m^2)
η	efficiency
T	temperature (ºC)
ΔT	temperature difference
m	mass flow rate (kg/s)
c_p	specific heat capacity (J/(kg K)

Subscripts

a	ambient
EL	electrical
T	thermal
PV	photovoltaic

1. INTRODUCTION

Technologies to harvest solar energy have been developing very rapidly over the last few years as of the increasing energy prices and the requirement for lower carbon footprint of buildings [1-6]. Among others, PV modules have become an important component of many solar energy systems and their share in the total generated electrical power is increasing significantly. An important factor influencing the PV cell efficiency is its temperature. An increase of a cell temperature has two consequences: decrease in the solar-electrical energy conversion efficiency and thermal fatigue due significant PV panel's body temperature throughout the day. At "the nominal operating cell temperature", the PV cell efficiency usually remains in the range of 6 to 15%. With a 1K cell temperature increase, the electrical efficiency of the PV decrease by about 0.25-0.5%, depending on the PV type [7]. Thus, by cooling the PV cell, the efficiency of the power generation could be improved. It is, therefore, important to cool down the PV cells in order to sustain their efficiency as high as possible. There are many solutions that can keep the cells at low temperature under various solar irradiation conditions. These cooling solutions were classified by Du *et al* [8] into two categories: air and hydraulic based cooling methods. In first group there are: passive cooling, naturally ventilated and façade systems, forced ventilated and façade systems. The hydraulic based cooling systems, or hydraulic PV/T systems, are implemented using liquid immersion cooling, water cooling, heat pipe cooling and phase change materials (PCM) systems. Air cooling is an implemented for buildings with ventilated facades. But, in such solutions, the heat transfer from the PV to the air is rather low and the PV temperature can reach temperature as high as 50^{o}C (or even higher based on the climate) during the summer [8]. Among the passive cooling systems, an interesting solution is cooling using PCM materials. It has been reported that stabilizing the temperature of PV cells at the level ensuring favourable effectiveness of the energy module can be achieved using PCM based systems [9]. Smith *et al* [9] findings demonstrated an increase of 6% in the PV electrical output by using PCM based cooling system in certain geographical regions. However, as these systems rely on storing the cooling effect during low temperature period to offset the heating effect of the PV when subjected to solar irradiation, such systems do not enable the use of the waste heat that is generated during the photovoltaic modules solar energy harvesting. The integration of the photovoltaic and thermal systems in the hybrid photovoltaic panels (PV/T) enables the conversion of both heat and electrical energies from solar irradiation simultaneously [10]. One option to achieve the PV/T system is by water cooling of the PV panels. Bahaidarah *et al* [11] reported experimental and numerical simulation results on cooling the PV panels using water and have demonstrated that by using the active cooling technique, the operating temperature of the PV panel decreased about 20% leading to an increase of 9% in the electrical efficiency of the PV panel. Active cooling techniques that utilise nanofluids have also been investigated and were found to provide higher cooling efficiency to water based systems [12]. In cold climates, active cooling using water would require special arrangements and add-ons to avoid freezing conditions for the water and the use heat pipe based cooling system becomes better suited [13]. The use of the heat pipe technology has been investigated extensively in recent years as of the efficiency of such system and the many advantages that it brings to the PV/T systems including but not limited to: multiple contingency, modular design and cost efficiency [14-25]. Gang *et al* [13;26;27] presented performance and parametric analysis of a novel heat pipe PV/T system in which a dynamic model of the HP-PV/T system has been presented and validated it using experimental results. Based on the presented model, the authors have demonstrated that the performance of HP-PV/T system increases with the increase of the flow rate, which is to be expected based on earlier research. Annual energy analysis of heat pipe PV/T systems have been reported by many researchers [26;28;29]. The reported work demonstrate clearly that solutions integrating the PV systems and thermal energy systems are important for high efficiency of the solar energy technologies. In addition, it is also clear from the reported research that the heat pipes technology has tremendous potential for wide utilisation used in PV/T. Having that in mind, it is only logical to move forward with the PV/T technology to have it integrated within the building envelope (BIPV), or to be as an energy active building envelope material as of the major advantages this will have on building envelope technologies.

Traditionally, the outer skin of a building has been viewed simply as a way of keeping the environment out; in cold climates this has meant cold and rain whilst in hotter locations it has meant keeping the heat out and in the large majority of the world a combination of both depending on time of the year. More recently with the occupants looking to reduce running costs and lower the carbon footprint of their buildings, the installation of solar devices to the outsides of building, trying to collect energy from the sun, have been common. However, there are several drawbacks to retrofitting products to a building not least of which is that the mountings often penetrate the skin and impair the very basic of functions, which is keeping the weather out. In addition to this the installation of different materials has a less than appealing look.

Having looked at the possibility of producing a building envelope that includes PV at manufacture rather than having it installed latter as an addition, it is hoped to overcome the visual limitations of retro fit. However this has its own drawbacks, by including the PV in the build the air flow to the PV is reduced and again the issues of trapped heat building up occur. All of these issues can be overcome by having the surface that the PV systems are installed on to be actively cooled. Making an actively cooled roof is a complicated setup taking into account the wide areas that has to be dealt with and the complications of the cooling system plumping and control. The ideal scenario would be to use flat heat pipe that will harness the solar energy and focus it is a small area where this heat can be absorbed using a suitably designed cooling manifold. Jouhara and Lester were the first to report such setup [30] where a novel flat heat pipe configuration was developed and used as a Building envelope to harness solar energy in thermal and electrical form in addition to the heat pipe itself being the Building envelope material. The new type of PV/T flat heat pipe is referred to as the PV/T Heat Mat. The heat mat utilisation converts the Building envelope from merely being a passive weather shield to an active component in the buildings energy generation, both electricity and heat. In addition, the utilisation of the heat mat enables 100% of the surface area that is facing the solar irradiation to be active as now gaps exist between the heat absorption elements.

In this paper, the performance of the new heat mat as an energy system that forms a building envelope will be reported and the benefits of the new heat mat, as a thermal system and as a PV/T units will be demonstrated.

2. THE FLAT HEAT PIPE (HEAT MAT)

The heat mat is complex multi-channel flat heat pipe that is fully described in a UK patent GB11410924.3 [30]. The new flat heat pipe design enjoys a unique internal finning methodology that allows efficient heat transfer from the above surface that is facing the solar irradiation to boil the heat pipe working fluid that flows up to the condenser section of the heat pipe that is cooled using a manifold. The manifold is attached to the back of the heat pipe using removable securing devices. A thermal interface material was placed between the manifold and the back of the condenser section of the flat heat pipe to reduce the interface resistance. The flat heat pipe or the heat mat is made as a thermal solar absorber and the PV/T system is made by bonding a PV layer on its front surface using thermally conductive flexible adhesive film. The whole setup of the heat mat is shown in Figure 1. Each heat mat is 4m in length and 0.4m in width.

3. THE HEAT MAT EXPERIMENTAL APPARATUS

In order to confirm the suitability of the new heat mat as a building envelope, a full scale building roof was constructed in Cardiff, UK with the new heat mats as the building envelope

materials. The construction setup can be seen in Figure 2. As it is illustrated, the roof was built using two types of heat mats, namely thermal and PV/T. The system schematic is shown in Figure 3 where it can be seen that an intermediate fluid (60% water and 40 Glycol) is used to cool the PV/T panels and to harness the heat from the thermal panels before delivering this heat to the heat pump system.
In order to achieve the maximum possible electrical output from the PV/T mats, the mats' cooling manifolds were connected in parallel to the water/glycol circuit in order to keep the working temperature of the mat as low as possible. The water/glycol flow is then forced through the condensers' manifolds of the thermal heat mats in series to achieve the highest possible coolant temperature under the available solar irradiation conditions before having the water/glycol flow returning to the heat pump system.

4. EXPERIMENTAL RESULTS AND DISCUSSIONS

4.1. Thermal output

Three heat mats were selected for this test. A heat mat with no PV on it and two PV/T heat mats one with cooling and the other without. Weather forecast predicted the 9th of September to be a clear day in Cardiff; therefore, this day was selected for the thermal test and was clear throughout the day.

The thermal output test was conducted by allowing the water/glycol to flow through each of the cooling manifolds of the thermal and the PV/T mats at a constant flow rate of 1 l/min. k-type thermocouples were used to monitor the heat mats working temperatures, the cooling flow inlet and outlet and the ambient temperatures. National Instruments data acquisition system was used to collect the data. The RH and wind speed were recorded and a Pyranometer was used to measure the subjected solar irradiation, in real time. The arrangement and the selected panels for the thermal test are shown in Figure 4.

As it is evident from the data in Figure 5, the thermal mats were superior to the PV/T mats from thermal energy harnessing point of view. This is to be expected as some of the solar energy will be reflected by the glass cover of the PV layer in addition to the added thermal resistance that is present due to the added adhesive that ponds the PV layer to the heat mat. The energy conversion efficiency was observed to be around an average value of 64% for the thermal mat and 50% for the PV/T mat. These efficiencies are very promising especially that no protection from convection to the ambient was provided as it is the case for most of the reported systems to date.

4.2. The effect of cooling on the electrical output from the heat pipe PV/T panels

To investigate the effect of cooling on the solar/electrical conversion from the PV/T heat mats, electrical output data from panels 1 and 2 (see Figure 4) were collected with the thermal test that is reported in the previous section, simultaneously. An electric heating element was used to consume the collected electrical energy from the PV panels. The consumed power was monitored in real time using a power meter. As it is evident, the cooling of the PV/T heat mats lead to an increase in the efficiency of the electrical output of about 15% when compared with uncooled heat mats. This enhancement is higher than the reported data [7], which suggest that the new heat mat is better suited for PV/T systems from electrical output point of view. This finding is believed to be due to the isothermal surface temperature of the heat mat that is secured by the heat pipe function. Also, it can be attributed to the very efficient cooling manifold that absorb the heat from the heat mats.

4.3. The effect of cooling on the temperature of the heat pipe PV/T panels

As can be observed from Figure 7, the temperature of the PV without cooling ranges between 40 and 58°C. This temperature was significantly reduced with the utilisation of cooling where the PV/T panel's temperature was kept between 28 and 33°C. The efficiency of the PV/T system is higher than the system without cooling (see Figure 6). It is also clear that the both panels (cooled and uncooled) started at the same temperature and when the solar irradiation was subjected on both, the effect of cooling became pronounced and the uncooled panel heated up at a relatively steep manner.

4.4. Daily average of thermal, electrical and cooling effects of the PV/T panels

The daily thermal output average, cooling effect and electrical output of PV/T panels (for 09.09.2014) operation of the presented system can be defined as follows:

The PV electrical power can be given from:

$$Q_{EL} = I \cdot U/A_{PV} \quad (1)$$

The amount of heat produced from PV panel is given as:

$$Q_T = m \cdot cp \cdot \Delta T \quad (2)$$

The electrical efficiency of PV panel is given as:

$$\eta_{EL} = \frac{Q_{EL}}{G} \quad (3)$$

The thermal efficiency of heat pipes panel is given as:

$$\eta_T = \frac{Q_T}{G} \quad (4)$$

The PV/T system energy efficiency is given as:

$$\eta_{EL+T} = \frac{Q_{EL} + Q_T}{G} = \eta_{EL} + \eta_T \quad (5)$$

The results are summarized in Table 1.

5. Thermal energy absorption from the ambient (convective gains)

As it has been demonstrated in the above sections, the new heat mat has been proved to be an effective PV/T to facilitate the solar energy conversion to thermal and electrical outputs. However, and due to its isothermal surface behaviour under any thermal fields and the fact that heat can be absorbed from a small area using the cooling manifold, the capability of absorbing the heat energy from the ambient to assist the heat pump, when no solar radiation is available, was tested in a controlled environment.

In order to carry out the needed tests in the controlled environment, a timber roof truss system with four mounted heat mats was erected in an ISO-certified environmental chamber, see Figure 8. The heat mats were inclined at 36°, mounted on a 1.0m high timber frame. Two panels had PV cells bonded to the upper surface. The total active roof area tested was 6.4 m2. The coolant that runs through the heat mats' manifolds was water/glycol mixture.

The laboratory tests were carried out in the environmental test chamber at ambient temperatures between -10°C and 30°C. The roof section was connected to a buffer tank inside the chamber (see Figure 8), and water heating/cooling plant outside the chamber to supply glycol to the buffer tank at temperatures between -14°C and 26°C.

Figure 9 shows the variation in absorption rate against the ambient / coolant temperature difference for different ambient wind speeds. The graph shows that the absorption rate increases as both the ambient / coolant temperature difference and the air velocity increase. It also confirms the ability of the heat mat for absorbing heat energy from the ambient. This heat energy will be elevated for domestic use by the incorporated heat pump.

6. Conclusions

A novel flat heat pipe solar collector type that can be utilised to harness solar energy and act as a building envelope is introduced. The new solar collector is named the "heat mat" as of its distinguished physical features. The heat mat has been built in full scale and a full size roof was built to test the suitability of such design. Three meat mats were fully instrumented to run energy and performance analysis on them where the first was properly cooled PV meat mat (PV/T), the second was uncooled PV heat mat and the third was a thermal heat mat with no PV on it.

The new roof was installed in Cardiff, UK. Weather forecast was used to identify a clear day, in which a comparative energy and performance analysis was conducted on the three heat mats. It has been observed that the new heat mat is not only efficient in solar/thermal energy conversion, but also was proven to be highly efficient in enhancing the electrical output of the PV layer that is placed on it when cooling was provided. From thermal point of view, the solar/thermal energy conversion efficiency was observed to be around 64% for the heat mat with no PV while this value was observed to be around 50% for the PV/T mat. The lower value for the PV/T is believed to be due to the solar radiation reflection from the protecting glass of the PV layer.

The effect of cooling on the solar/electrical energy conversion of the PV/T heat mats was shown to increase the PV/T's electrical output by about 15% when compared to uncooled PV heat mats.

The heat mat has also been proved to be an efficient thermal energy absorber from the ambient even without solar radiation. This ability is believed to enhance the energy efficiency of the incorporated heat pump system.

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Figure 1. The heat mat setup


Figure 2. The heat mats' based solar roof installation

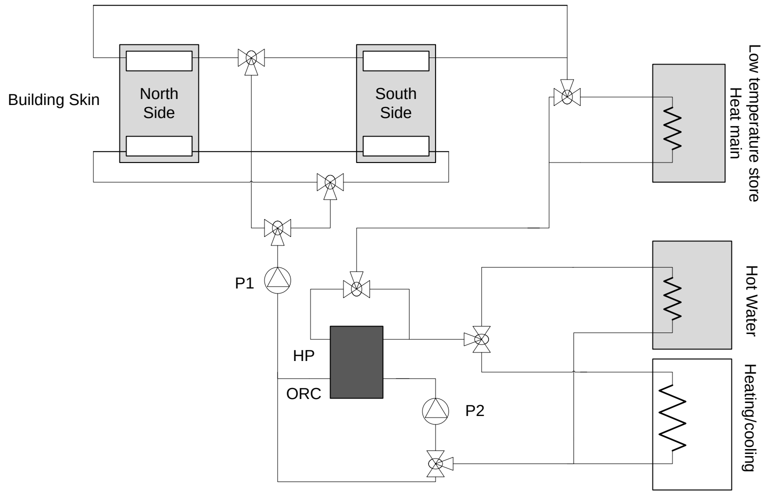

Figure 3. The connection diagram of the solar roof north and south sides with the heat pump and storage system

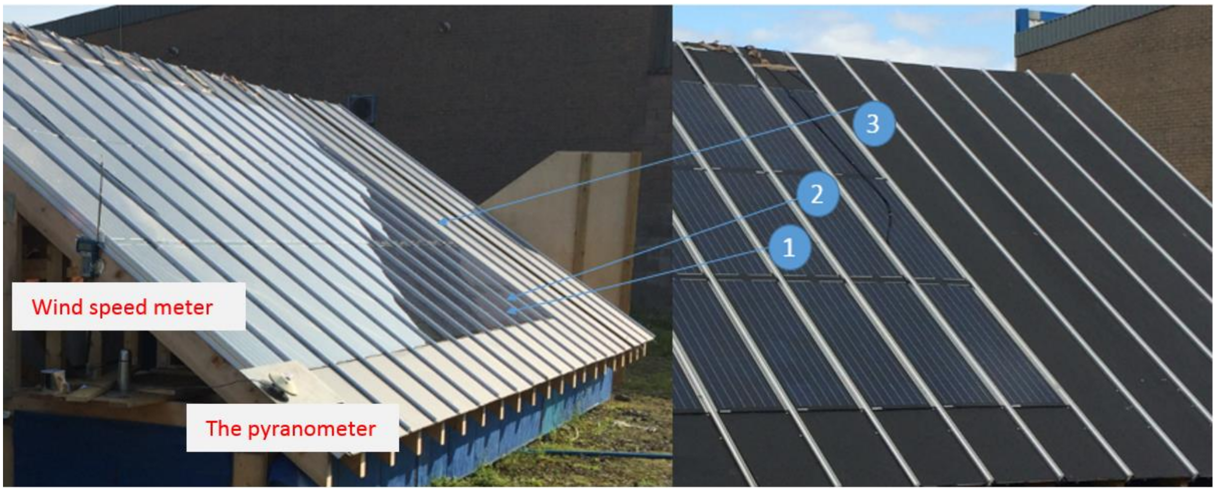

Figure 4. The selected panels: 1- Cooled PV/T, 2- Uncooled PV & 3- Thermal

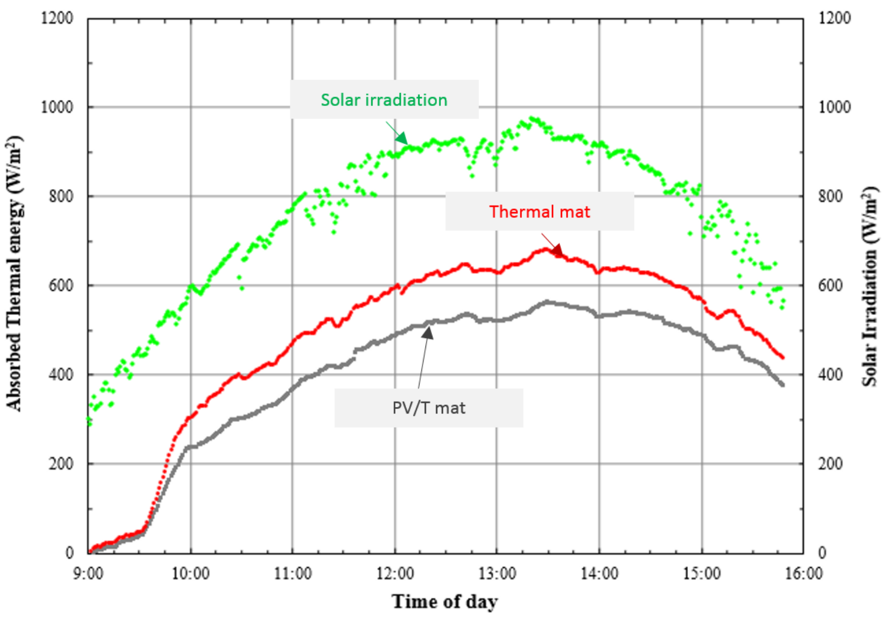

Figure 5. The thermal output test on thermal mat and PV/T mat. The date: 9/9/2014. Location, Cardiff, UK.

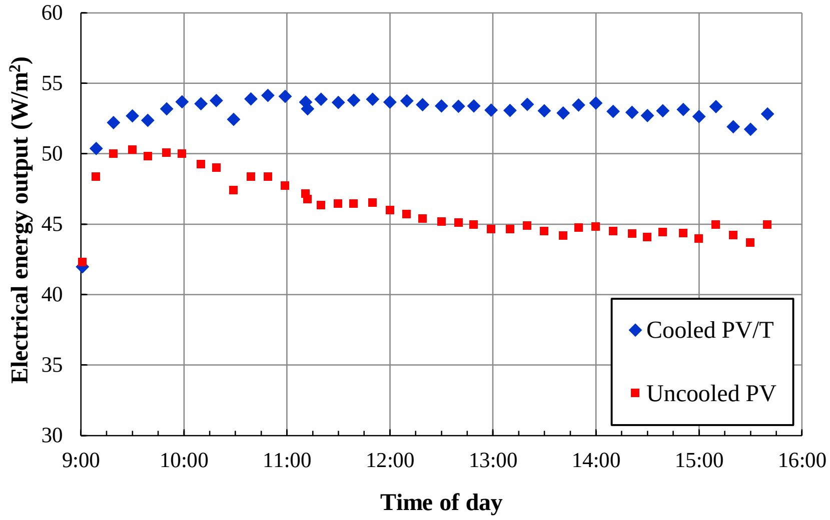

Figure 6. The effect of cooling on the electrical output from PV/T heat mats

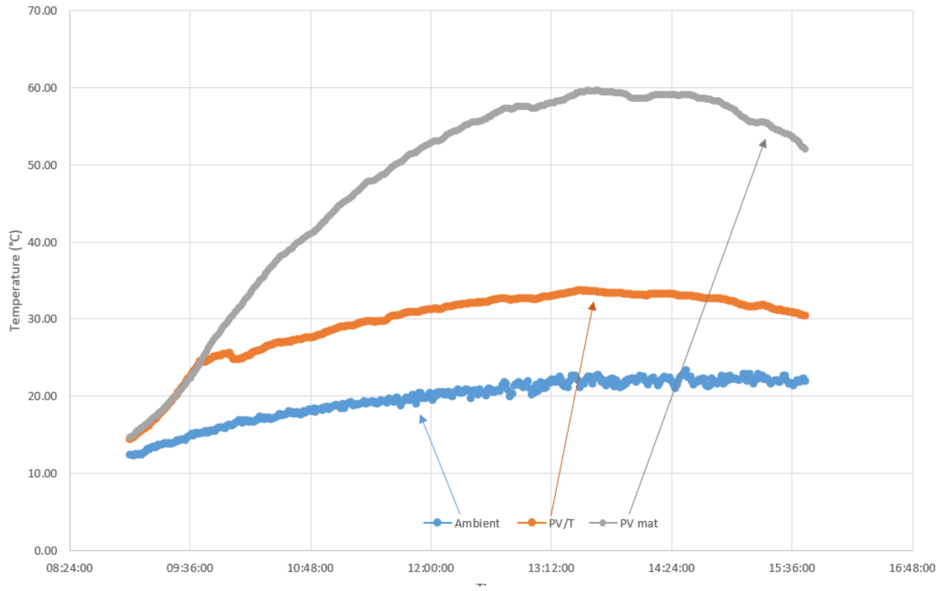

Figure 7. The effect of cooling on the heat mat temperature for PV and PV/T cases

Figure 8: The thermal energy absorption test in an environmentally–controlled chamber

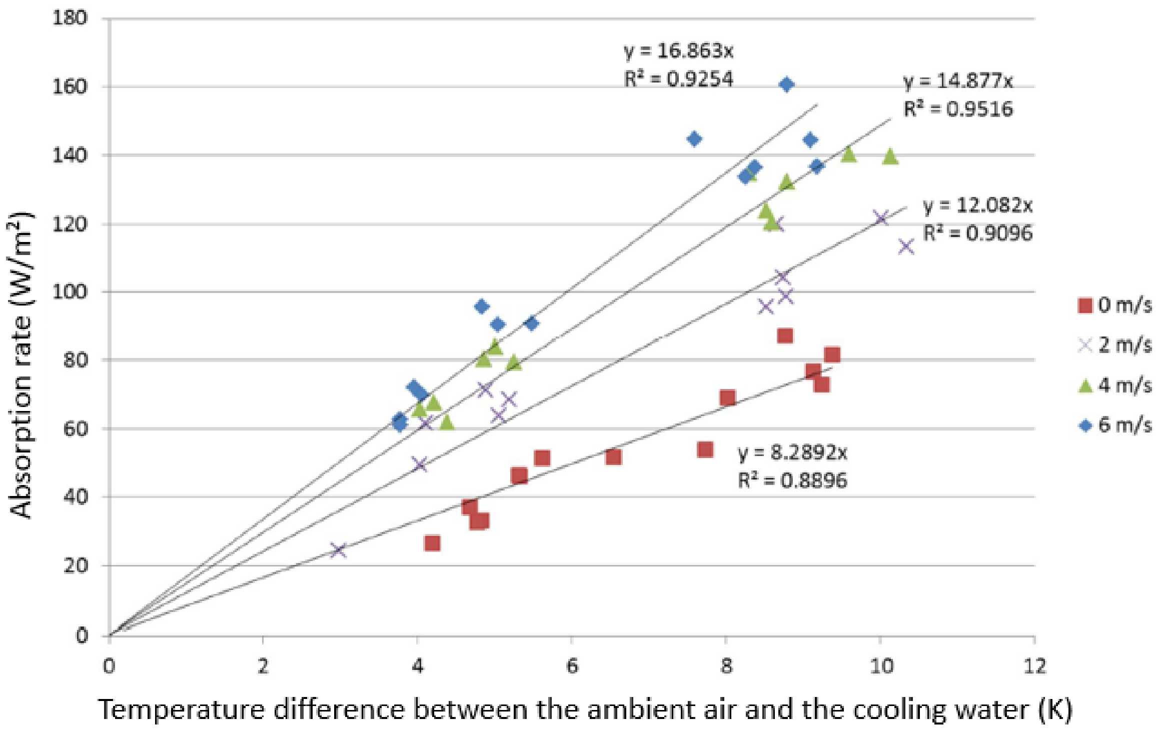

Figure 9: Heat absorption rate by the heat mats from the ambient at various temperature differences and air speeds.

Table 1. Daily average of thermal, electrical and cooling effects of the PV/T panels (for 09.09.2014)

Parameter	Type of installation	Date: 09.09.2014 Hour: 9:00-16:00
G, kWh/m^2	-	5,02
T_a, °C	-	19,5
Q_{EL}, kWh/m^2	PV PV/T T	0,31 0,35 -
Q_T, kWh/m^2	PV PV/ T T	- 2,49 3,24
η_{EL}, %	PV PV/ T T	6,1 7,0 -
η_T, %	PV PV/ T T	- 49,4 64,0
η_{EL+T}, %	PV PV/ T T	6,1 56,5 64,0
T_{PV}, °C	PV PV/ T	47,2 29,3
$(\eta_{EL\ (PV/\ T)} - \eta_{EL\ (PV)})/\ \eta_{EL\ (PV)}$		15 %