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

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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.

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 6–15%. With a 1 K 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 PCM (phase change materials) systems. Air cooling is an implemented for buildings with ventilated facades. But, in such

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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 (°C)
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

solutions, the heat transfer from the PV to the air is rather low and the PV temperature can reach temperature as high as 50 °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 demonstrates 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 Fig. 1. Each heat mat is 4 m in length and 0.4 m in width.