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The performance of a heat pipe based solar PV/T roof collector and its potential contribution in district heating applications

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ABSTRACT

Photovoltaic–thermal water collectors have the ability to convert solar energy into electricity and heat, simultaneously. Furthermore, the combination of photovoltaic–thermal solar collectors with a water cooling system can increase significantly the electrical and thermal efficiencies of the system, which can improve the total thermal efficiency of buildings. In this paper, the findings of six experimental configurations of solar-thermal collectors are presented and analyzed. Five of the solar-thermal panel configurations were implemented with a cooling cycle. Two of the solar-thermal panels were equipped with monocrystalline silicon modules, the other two collectors were equipped with polycrystalline silicone modules, one of the collectors was based on heat pipe technology and was equipped with a cooling system, while the last collector did not include any cooling cycle. The duration of the experiments was four days during the September of 2014 and they were conducted under different solar radiation conditions. The second part of the paper presents the simulation results for five of the solar-thermal panels connected with a cooling water tank (volume of 500 L), a domestic hot water tank (volume 350 L) and a water–water heat pump, in terms of covering the hot water demands of a single family dwelling. The results showed that the hybrid solar collectors would be able to cover approximately 60% of the dwelling's hot water needs for days with low levels of solar radiation, while for days with high solar radiation they could cover the hot water requirements of the family by 100%.

1. Introduction

The combination of photovoltaic/solar and thermal energy systems into one integrated system is known as a hybrid PV/T (photovoltaic/thermal) solar system. These systems are characterized by two distinguished parts; the photovoltaic technology part, which converts the thermal energy of the solar radiation into electricity, and thermal technology part, which facilitates the energy conversion from solar radiation to thermal storage [1,2]. Thus, the PV/T solar systems can produce simultaneously electricity and heat. The conventional configurations of photovoltaic and solar-thermal systems have both advantages and disadvantages, but once combined together as PV/T panels they offer an alternative and very promising system for low-energy consuming residential applications [3–5].

PV/T collectors vary in designs and technical aspects according to the resigned application [6,7]; however, all of them shall follow the requirements of architectural integration, as they are set by the International Energy Agency, which states that integrated solar thermal collectors can be installed either on the buildings' front face or on their rooftops [8,9].

Flat plate PV/T collectors can be classified into the following categories, depending on the type of working fluid used: water PV/T collectors, combined water/air PV/T collectors and air PV/T collectors. Another categorization of PV/T collectors can be done based on whether or not an absorber collector underneath the flat plate is present. In any case though the basic parts of every flat plate PV/T collector are a glass cover (glazed or unglazed), solar

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cells, encapsulated materials and the absorber collector (optional). The collectors' absorber has a significant function in the PV/T system; it cools down the PV cell and uses the waste thermal energy to produce hot water or hot air. In this way the efficiency of the PV module increases significantly [4,10].

The hybrid PV/T systems can address issues like the low efficiency rates of PV collectors [11], their high cost, the architectural uniformity of buildings and the limited space on rooftops, which until today consist the reasons that hold back the wider implementation of solar panels in buildings. The hybrid PV/T collectors offer higher electrical efficiency due to their cooling system, they provide architectural uniformity by aesthetical designs, they minimize the required space on rooftops and they are characterized by a reduced payback period [12,13]. Combination of water and/or air type collectors can be categorized according to the flow pattern of the water or air. In water type PV/T collectors, the parameters under consideration are the shape of the collector, the channel size and the type of the working medium, the flow pattern of the medium and the absorber technology.

Temperature is another important factor influencing the performance of PV collectors. An increase in the temperature of the PV panel causes the decrease of the collector's efficiency and its exposure to high thermal stresses. The increase of the PV panel's temperature by 10 °C can lead to a decrease of its electrical efficiency by 2–5%. For example the typical electrical efficiency of PV panels under nominal operating temperature of 25 °C is 15%. When the PV temperature increases to 45 °C, the electrical efficiency of the panel is in the range of 13.5–14.4%, depending on the type of PV panels [14,15]. The integration of PV panels, with thermal collectors as hybrid photovoltaic thermal PV/T panels enables more efficient cooling of the panel and the simultaneous production of thermal and electrical energies. Some of the most widespread PV/T collector technologies or heat exchangers are based on water cooling or air cooling systems [14–17]. According to the literature the use of active cooling techniques is able to decrease the operating temperatures of the PV panels by 20%, while to increase their electrical efficiency by 9% [18,19]. A popular cooling system with great application potentials is the integration of PV panels with heat pipes [20,21].

The heat pipe is a structure with very high thermal conduction that enables the transportation of heat, while maintain almost constant temperature. Heat pipes are considered to be thermal super conductors due to the high heat rates they transfer across small temperature gradients. On their simplest form heat pipes are called thermosiphons and their operation relies on gravity, whereas the heat is transferred only from the lower to the upper end of the pipe. The heat pipe which allows the bi-directional transfer of heat is called wickless. The main structure of heat pipes is an evacuated tube partially filled with a working fluid that exists in both liquid and vapor phase. Fig. 1 represents the basic steps of operation of heat

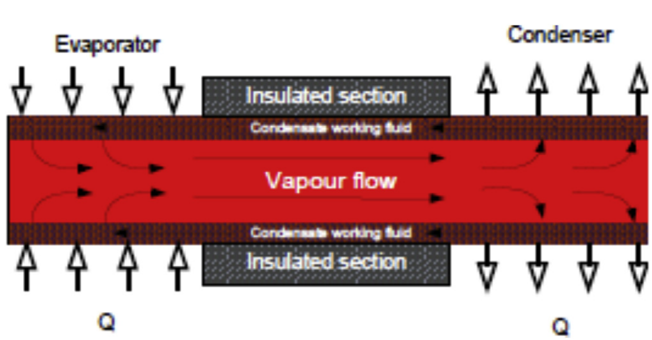

Fig. 1. Heat pipe exchanger's working cycle [21].

pipes. The bottom part of the heat pipe is the evaporator and the top part is the condenser. When a high temperature is applied at the evaporator section of the heat pipe, the working fluid existing in the liquid phase evaporates and flows with high velocity towards the cooler end of the pipe – the condenser. As soon as the vapor reaches the condenser section, condenses and gives up its heat. Then the liquid working fluid returns to the evaporator part of the pipe, by the influence of gravity [22]. A series of straight heat pipes joined in one structure can be considered as a heat recovery device. Its advantages are high thermal conductivity, passive and reliable operation, uniform temperature distribution, affordable cost and no need for external pumping system as in the conventional exchangers.

Heat pipe based heat exchangers find application in many industries as heat recovery and energy savings systems, while their operation has been investigated by several researchers. In his paper Jouhara examines the potentials of energy and cost savings in conventional means of dehumidification, by the incorporation of a wraparound heat pipe heat exchanger [24]. A year later Jouhara and Meskimmon examined the energy savings possibilities in air handling units, by implementing a wraparound loop heat pipe heat exchanger in the unit [25]. Another experimental investigation of Jouhara et al. regarding a heat exchanger of finned water-charged wickless heat pipes in a modified inline configuration was carried out [26]. Finally, in another paper Jouhara proved that the combination of heat pipe based heat exchangers in air conditioning systems can cool and dehumidification the outside air prior being direct supplied to the system for ventilation [27].

Freezing and corrosion of the heat pipes can be eliminated by carefully selecting the proper working fluid. Hence, heat pipes and solar collectors can be incorporated into a compact design of PV/T collectors. Performances of PV/T systems with different water loads per unit collecting area were also studied [28].

The reuse of the waste thermal energy produced during the cooling process of the solar PV panels remains a challenging aspect of hybrid collectors. To ensure high cooling efficiency the cooling temperature of the collector should be around 25 °C; the integration of a heat pump in the PV/T system can facilitate the above [29].

2. The experimental system

2.1. Test bench

The experimental apparatus was sited in Cardiff, UK, where an innovative design of flat heat pipe solar hybrid (PV/T) collector mat with unique internal finning pattern was tested. The flat heat pipes were made from aluminum as the shell material and ammonia as the working fluid. The tests were carried out for four days during the September of 2014 for different weather conditions. The solar panels were placed on a specially constructed apparatus which simulated a full-scale rooftop, facing South with an inclination of 51°. The experiments were carried out for six flat heat pipe solar panels, sprayed with high emissivity paint to operate as thermal solar absorbers. Four of the panels worked as PV/T systems with a PV surface layer, of which two PV/T collectors were equipped with monocrystalline silicon modules and the other two with polycrystalline silicone modules. One of PV/T collectors equipped with the monocrystalline silicon modules and one of PV/T collectors equipped with the polycrystalline silicone modules were cooled by attached manifold on the heat pipe condenser side. To reduce the interface resistance, thermal interface material was placed between the manifold and the heat pipe collector. The construction of the panel and its cross section are shown in Fig 2 and Fig 3. Each panel had a length of 4 m and 0.4 m in width.

The working fluid flow rate was constant through each of the cooling manifolds and equal to 1 L/min. To monitor the thermal

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