Experimental Performance Investigation of Novel Flat Plate Collector for Hybrid Photovoltaic/Thermal Solar (PV/T) Module

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Abstract - *The prototype here presented is specifically designed by taking into consideration the domestic single family electrical and thermal energy requirements. A water-based hybrid solar collector is designed according to top technologies available in literature: single-glazed collector composed by Poly-crystalline silicon cells directly integrated with a novel aluminum rectangular spiral flow flat plate absorber. The preliminary design choices, concerning absorber plate layout, cells number and configuration, insulating materials, casing structure and building integration are taken into consideration. An appropriate mathematical model, developed and validated on an analogous amorphous hybrid collector, is adopted and implemented in MATLAB, with further modifications according to the prior design. The final layout of the hybrid collector is the result of the preliminary design. The solar energy incident on the flat plate collector have been analyzed to obtain higher insolation input and optimum design parameters like tilt angle, module orientation has been implemented.*

Key Words: **renewable energy, solar energy, hybrid collector, photovoltaic-thermal collector, PV/T**

1. INTRODUCTION

Solar energy is generally exploited by two matured technologies: solar thermal to produce thermal energy and solar photovoltaic to produce electricity. Solar thermal technology is used in various domestic, agricultural and industrial applications and it is available in the market at a very effective cost. As well, solar photovoltaic technology is one of the most developed solar technologies, but commercial PV electric efficiency is quite low. Usually it is in the range between 5% for thin-film and 20% for single-crystalline, while the rest of solar energy turns into heat and causes the increase of PV cell temperature [13]. It is possible to adopt a heat recovery system on the back of panels. This concept of combining solar photovoltaic and Thermal system (Combined Heat and Power production) is known as Hybrid Photovoltaic/Thermal (PV/T) collector system [14]. A Hybrid PV/T solar module consists (called PV/T module henceforth) of PV panel that performs the function of generating electricity and collecting thermal energy incident on it and a collector which performs the function of extracting this incident heat in the form of useful heat energy from the PV panel. Further, this thermal energy is utilized as waste heat recovery for heating water or air. This results in increased Electrical efficiency of the PV module. Various studies [6][7] reached the conclusion that a well-design hybrid PVT system can achieve better performances compared to the separated production of thermal and electric energy. For these reasons, the largest area of interest for hybrid PVT systems is the domestic one, where it is important to produce electricity and thermal energy with compact products, suitable for small roof surfaces [8]. The recovered heat can be used for different low temperature applications such as domestic hot water (DHW) production, space heating and cooling (post-heating or desiccant wheels) depending on the season, thermal storage [9], desalination [10], in the agricultural industry [11] and pool heating [12], etc. while domestic electricity demand is covered by photovoltaic cells production. The solar thermal collector is main element of the PV/T module. The presented paper studies a novel type of flat plate solar thermal collector made from aluminium sheet. In this thermal collector spiral flow design is used for even absorption of heat and maximum electrical efficiency of the PV panel.

The Literature encompasses several studies on the collector design and analysis. The study on different absorber design is [1] discusses Oscillatory Flow design, serpentine flow design, which are limited due to uneven temperature distribution. The spiral flow design displayed the optimum temperature distribution. The investigation of both Flat plate absorber and Sheet and Tube absorber design was done. The investigation presented Flat plate design outperforms the Sheet and Tube design[2]. The Flat plate design generated 3% more electricity and covers 3% more thermal demand on annual basis, at 21% lower PVT collector cost. This results due to the surface contact of the Flat plate absorber. Hybrid and non-hybrid PV systems for electricity generation and concluded that the hybrid PVT system generates 38% more electricity and has more chances of success[3]. He added that the hybrid PV/T system is economically viable in places with low temperature water use, like domestic household or dairy industries.

1.2 Problem Statement

The Project is aimed at designing and developing an innovative hybrid photovoltaic-thermal (PV/T) solar collector module, capable of generating simultaneously electricity and thermal energy used for water heating. . The design of module is done taking single family domestic water heating requirements into consideration.

1.3 Scope

PVT collectors have different applications with respect to region, because of various climates, terrestrial and cultural boundaries. For example where the climate is cold the mostly used are PVT/a systems in building integrated applications to lower the temperature of PV systems with air and supply the hot air for space heating. In warmer climates PVT/w systems are mostly used for heating water for domestic uses [15]. PVT products suit a wide range of applications and market sectors. According to the roadmap, the largest market potential of PVT lies in PVT/w for domestic sector (about 90% of the current market of solar collector). In short terms the customers can be from the single-family houses for the domestic hot water systems to the multifamily buildings, where the hot water demands are more stable. For the intermediate future, the possible markets are direct space heating, swimming pool heating and large hot water systems for both collective and utility applications and heat pump integration [5]. A water-based hybrid solar collector is designed for domestic water heating and electricity generation with an increase in overall efficiency.

For real-building project applications, the PVT/a system were more readily adopted in the European and North American markets though the higher efficiency of the PVT/w system has been confirmed. Anyway, the numbers of commercially available collectors and systems are still very limited. Actually, the main bottlenecks for the commercialization of PVT products are the lack of economic viability, public awareness, product standardization, warranties and performance certification, installation training and experiences. It is important for the reliability of the technology, which requires further research and development works on new products, including thermal absorber design and fabrication, material and coating selection, energy conversion and effectiveness, performance testing, system optimization, control and reliability [16].

2. PV/T DESIGN

2.1 Absorber Design

Absorber plate technology and channels shape and arrangement, are some very important design features, since they affect both electrical and thermal performances. Nevertheless, the choice of the correct absorber typology has to be also taken considering manufacturing process, reproducibility and costs. Absorber technology as reported there are many different solutions for heat recovery. Sheet-and-tube structure and flat-plate tubes are the most diffused absorber technologies in solar thermal application. Roll-bond absorbers and micro-channel arrays are the most suitable choice due to their higher performances. A flat plate absorber has been chosen for many reasons. First of all those kind of thermal absorber ensures very high thermal exchange performances, even when made of aluminum instead of more expensive and thermal conductive copper [5].

2.2 Channel Configuration

Different channel configuration have been designed & analyzed in the literature [4] with the help of Microsoft excel with parameters like solar radiation, ambient temperature, and flow rate conditions and are compared. Among the many configuration of channels, serpentine and harp (parallel) are the most widely used for conventional solar thermal collectors. The flow rate and its sharing between pipes affect the temperature of heat transfer fluid and temperature distribution along the absorber plate. In particular, temperature distribution through the pipes is not uniform in both configurations. As a consequence, each PV cells placed on different portion of the absorber have a different temperature and, thus, a different electrical performance. Serpentine absorber reaches higher temperature average and gradient than the harp configuration. Moreover they are characterized by higher pressure drops and consequently lower flow rate than harp configuration in order to avoid excessive electricity consumption of circulation pump. On the contrary, parallel pipe configuration, ensures slow temperature gradients between input and output and good temperature distribution on the whole absorber surface, with electrical and thermal benefits on PVT collector efficiency. For these reasons, thanks to a more homogeneous thermal distribution and to lower average temperatures, harp absorber is more suitable for PVT application than serpentine one [4]. From comprehensive analysis of different channel configuration designs, spiral flow design is chosen as it has highest thermal and electrical efficiency.. Spiral flow design allows uniform cooling of entire area of PV panel, which directly improves the performance of a PV panel.

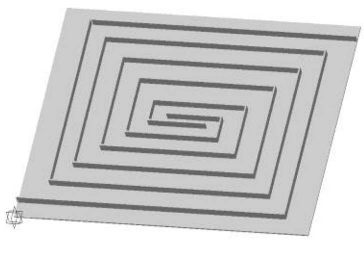

Fig 1 – 3-D Cad model of the novel spiral flow absorber

2.3 Final Absorber Design

The design of the aluminum flat plate rectangular channel spiral flow absorber adopted for this hybrid collector is reported in Appendix A, in Fig. A. The absorber plate has a width of 32.6 cm, length of 41 m and a thickness of 1 cm. It has two 1 cm circular shaped inlet and outlet. Flat plate absorber dimensions has been though to allow the presence of a commercial Loom solar panel having 36 PV cell cutouts distributed in 18 rows with 2 cells each, in order to obtain a high peak-power collector. In particular, a high collector length has been chosen to enhance thermal performance and effectiveness of heat exchange, since in general, a longer channels result in a better flow distribution. Regarding channels dimensions, square shape channel flow cross section area has been chosen, as it has superior thermal performance characteristics compared to other dimensions analyzed in the literature [2]. Flat plate absorber gives a denser channel distribution which drives the most uniform temperature distribution across the PV panel. The novel absorber 51 designed has 27 channels to flow across the length side which allows more water turns result in high temperature. However, for manufacturing limits the number of channels provided in the absorber. Spiral flow flat plate absorber was produced by attaching the individual channel fins on to the aluminum plate by means of thermally adhesive glues, which provides strong adherence, with leak proof advantage. Then it was packed with backside aluminum plate by means of the same glue, the rubber seal is provided to achieve 100% leak proofing of absorber. Further experimental investigation has been carried out to check leakages and fluid pressure bearing capacity. It was tested OK in these checks.

Fig 2 – Actual Spiral Flow Absorber

2.4 Photovoltaic Panel

The photovoltaic cells convert diffused and concentrated solar radiations into direct current (DC) through the bombardment of photons on the photovoltaic semiconductor panel.. Solar energy of 1.08 X 1018 kWh reaches the earth's surface [17]. About the total 100% solar energy incident on the earth surface, there exists a 38.3% visible light, 8.7% ultraviolet and 47.4% infrared (IR) electromagnetic radiation [18]. However, the photovoltaic cells responds to only a small portion of the visible solar spectrum, which is equal to or higher than the band gaps of the PV cell [19]. Various photovoltaic technologies have been described; each one has its pros and cons. Main differences concern nominal efficiency, temperature dependence of performances, annual yield decay, range of useful wavelengths, cost of purchase and reliability. The objective is to design a solar collector which guarantee the maximum electrical yield for square meters covered, in order to fit the domestic electricity demands as well as possible and minimize electricity withdrawals from the grid. The optimal choice from electric point of view is crystalline silicon technology. Thermal yield is important as well for hybrid systems. Absorption coefficients are around 0.9 for single-crystalline silicon cells and 0.85 for poly-crystalline silicon cells. In fact sc-Si cells have lower reflection losses than pc-Si cells and present a higher absorption in the whole range of the solar spectrum, because of a more homogeneous surface texturing [4].

For both thermal and electrical reasons, mono-crystalline silicon cells are superior to polycrystalline silicon cells. However due to availability of polycrystalline silicon solar panel, it has been chosen for the PVT fabrication. In particular, *Loom Solar Panel* is used. Panel dimensions are 450 x 350 mm, 36 PV Cell cutouts with 155 x 20 mm size each. Power at maximum power point (*Pmpp*) is 20.2 W and electrical efficiency of a panel is 17.94 %. Solar panel consists of a single glass attached to the PV cell. & it is manufactured with EVA encapsulation on both sides.

Fig 3 – Looms PV Panel Specifications

2.5 PV/T Integration and Assembly

Photovoltaic Loom solar panel is integrated at back side with the flat plate PVT collector by using thermal Adhesive integration technique. Silicone is used for integration of both modules, as it has superior qualities explained in the previous section. A 2 mm layer is sandwiched between PV & absorber module with taking proper care of air tight, bubble free module. Then the combined module is allowed to dry the solution and proper adhesion in sun rays for 2 – 3 days. After which it is tested for number of parameters like its strength, stresses at high temperature etc. finally a Photovoltaic Thermal collector module is ready for onsite assembly & operation.

Fig 3 – Complete Absorber module

Fig 4 – Thermal collector module with PV panel (PVT module)

3. EXPERIMENTAL SETUP AND INVESTIGATION

3.1 Basic Experimental Setup

The experiments were performed on the roof of the domestic apartment at Talegaon dabhade (18.7376°, 73.6747°). Actual experimental setup is as shown in figure 6. A complete setup was arranged to assess the electrical and thermal performance of PV/T solar module. It has two units, a PV/T module and a storage tank unit. The two units are connected by pipes/hoses. Two separate modules were used in the study for comparison. As discussed in the section, first module is a Flat Plate Rectangular Box Spiral flow Channel Absorber PV/T collector module. The commercial solar photovoltaic panel is used to satisfy required dimensional specifications. Commercial Loom solar panel consists of poly-crystalline silicon solar cells of 36 cut outs are arranged in parallel in a double string to obtain theoretically 20 Watt power electrical energy. EVA is used for PV encapsulation to and back side of PV panel.

Fig 5 – PVT module and PV Panel

Fig 6 – Experimental Setup of a PVT collector System

Tempered glass is covered over panel. The absorber is made up of aluminum 3003 grade. The rectangular matrix enhances more area enclosed with PV panel. This obviously helps in extracting more heat from the solar panel. Silicone is used as thermal integrator between PV panel and Absorber. The total aperture surface area of the cells is 0.1116 m2 & Panel dimensions are 450 × 59 × 350 mm. The second module is a commercial solar PV panel without any modification taken into consideration.

The collectors are placed at different optimum angle for each month at south direction. The both panels are placed very near to each other so that same irradiation incident on them. The cells used in the PV and PV/T module are Poly–crystalline cells. The output from each panels are fetched through wires which are connected to a separate multimeters. The current from all modules are measured by connecting multimeters in series to the modules and the voltage is measured through another multimeters which are connected in parallel to the modules.

Experiments were conducted on 18 & 19 march 2020, in which readings of various parameters are taken throughout a day, in order to get results variation throughout a day with respect to atmospheric conditions, solar irradiation throughout a day, different parameters measured are as follows

1. Inlet & Outlet temperature of water from PVT module
2. Tank water temperature
3. PV & PVT collector front & back surface temperature
4. Atmospheric temperature
5. Short Circuit Current & Open Circuit Voltage
6. Solar radiation incident on collector module

Table -1: Specifications of the Collector modules

Flat Plate square shaped spiral flow Channel Photovoltaic/Thermal solar Collector	Collector Dimensions : 450 × 350 mm Absorber Dimensions : 335 × 405 mm Absorber Material: Aluminum 3003 Grade Effective Area: 13.57 cm^2 Module Power : 20 Wp
Loom Solar photovoltaic panel	Module Dimensions: 450 × 350 cm Cell Area: 11.16 cm^2 Cell Type: Polycrystalline silicon solar cells Conversion Efficiency: 18.1 % Module Power : 20 Wp
Water Storage Tank	Type: Vertical Cylindrical type Capacity: 30 liters Thermal Insulation : Foam

3.2 Experimental conditions

The experimental conditions suggest the location, Longitude and latitude of the place where experiment was conducted. It also mentions the details of Solar panel including its tilt angle and direction of the face.

Table 2 – Experimental Conditions

Location	Talegon Dabhade, Pune
Latitude	18.7376°
Longitude	73.6747°
Tilt Angle	30°
Direction	South

3.3 Instrumentations

In order to measure the temperature of water stored in storage tank, inlet and outlet temperature of the water at the PV/T module & ambient temperature, the calibrated thermistors / copper constantan thermocouples are used. The IR thermometer is used to measure the surface temperature of PV & PV/T module. Hourly solar radiation is measured with the help of solar power meter with the same tilt angle as that of modules /data from metrological department. A Water Flow meter is used to measure the flow rate of the water flowing through the PVT module. Various temperature sensors are placed at inlet and outlet of both the tank and the collector to measure the variations in water temperature accurately.

4. RESULTS AND DISCUSSION

In this study, the novel PVT hybrid collector module & a reference PV panel are experimentally investigated by varying different operating parameters. The performance of the PVT system is then evaluated and compared with the reference PV panel from the data achieved. The data were recorded from 8 AM to 5 PM in the interval of 20 minutes for the complete sunny day. This study was conducted on 19 may. The results achieved are explained in detailed in this section.

4.1 Analysis of PV and PV/T collectors' temperature

The initial conditions of ambient temperature and inlet water temperature are 27°C and 24°C respectively. With the increase in the ambient temperature and variation in solar radiation, the PV and PVT module temperatures of different layers are increased in the pattern as shown in chart 1 and chart 2. The effect of solar radiation incident on the front surface temperatures of PV and PVT collectors is shown in the chart 1. The model has allowed the optimization of some components and the configurations of some sub-components. The mathematical model of a covered a-Si PVT which has been adopted here is modified as per requirement and its implementation in MATLAB is presented.

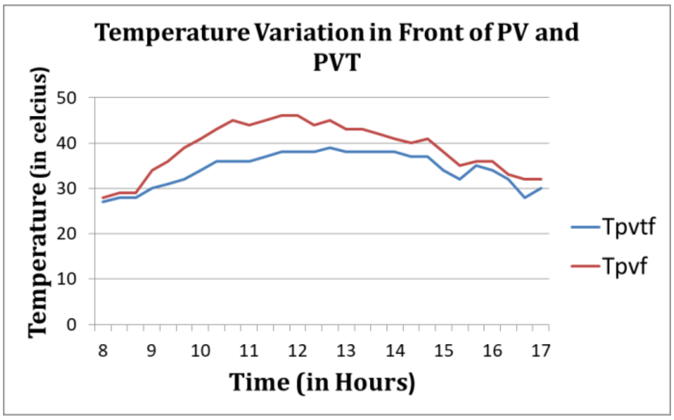

Chart – 1: Temperature Variation in the Front Surface of reference PV Panel and Novel PVT Collector throughout a day

It can be seen from the chart 1, which the temperature of the front surface of the PV panel goes on increasing till the mid-day, on the other hand, the temperature of the front surface of the PVT module remains slightly increases & then remains same throughout a day. Also from chart 2, it can be seen that the back surface temperature of a reference PV panel increases throughout a day; this is because of an accumulation of heat into the panel. As Tedlar absorbs extra irradiation coming directly to Tedlar caused by packing factor of PV modules, which further increases the temperature of Tedlar back sheet. However the temperature of back surface of the PV module of PVT collector remains same throughout a day, this is because the water flowing through the channels absorbs excessive heat and allows the PVT module to the less temperature over different layers. Again due to more absorbance of a Tedlar backsheet, it has been removed while fabricating PVT collector. Also from chart 1 and 2, it can be seen that the temperature of glass cover is less than the temperature of Tedlar backsheet due to the different coefficient of heat transfer, which 7.41 and 5.81 W/m2 are respectively resulting in higher dissipation of heat from the glass than the Tedlar in natural convection.

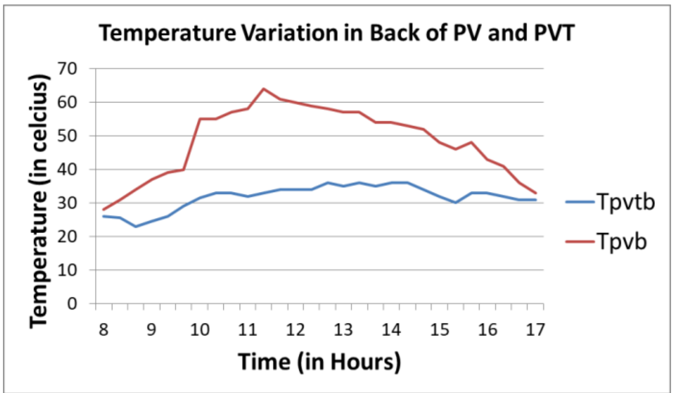

Chart 2 - Temperature variation in the back surface of reference PV Panel and PVT Collector throughout a day

4.2 Effect of volume flow rate on system temperature profile

The PV module taken for reference is without any cooling except natural convection, where it released partial amount of heat to the surrounding due to the temperature gradient. Therefore it resulted in the maximum temperature of 64°C at the mid-day, which indirectly affected the electrical performance of the PV panel. Again there is non-uniform temperature distribution in the surface area of PV panel, as there is maximum temperature at the centre position than that of edges. This is because of an effective natural convection at the surface edges as edges releases heat from all the directions.

In case of PVT collector, it has been observed that, due to forced convection by circulation of cooling fluid, temperature of PVT module remains less throughout a day. This resulted in an improved electrical performance than the reference PV panel. The maximum temperature of a PVT recorded at front and back surfaces are 39°C and 36°C respectively. The rate of volume flow through channel has an significant effect on the surface temperature. We have evaluated surface temperature for different volume flow rates from 0.5 LPS to 5 LPS, it was observed that, as the volume flow rate increases, the PVT surface temperature drops by a significant gradient. It means, higher the volume flow rate is higher the removal of heat from collector's surface.

4.3 Volume flow rate effect on electrical performance of PVT collector

The electrical efficiency of a photovoltaic drops as the temperature of PV module rise due to high irradiation. Volume flow rates across the PV modules can reduces the heat to a certain level to cool the cells in the module for their enhanced electrical performance. Thus to obtain optimum value of volume flow rate, we have experimented different volume flow rate across the channel, it was observed that, the electrical performance increases with increase in the volume flow rate. This is because of the reason that cell temperature is higher than the inlet temperature of high volume flow rate water, which resulted in the removal of maximum heat from the PV module. Higher volume flow rates reduces the cell temperature prominently, consequently, PV voltage increases noticeably while the current reduces to some level, which causes an increase in electrical efficiency and output power of the PVT system.

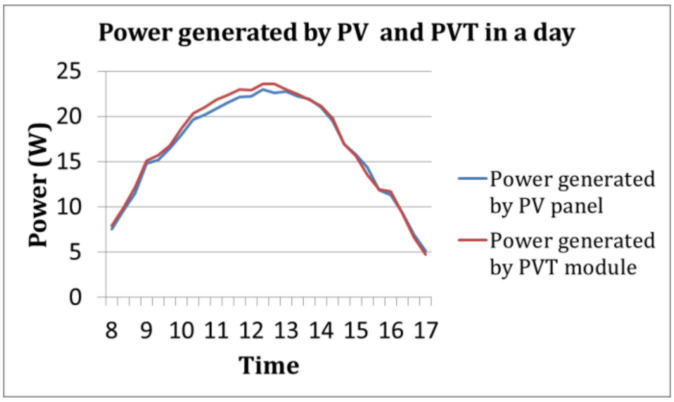

Chart 3 - Power generated by novel PVT collector and reference PV panel throughout a day.

Chart 3 shows the variation in power generated by individual PV panel and novel PVT collector module. From above figure, it is observed that the output power generated by novel PVT collector is significantly increased than the reference PV module. From chart 4 and 5, it was shown that, the open circuit voltage induced in a novel PVT collector module is more than the reference PV module. This is because of the inverse relation between the open circuit voltage and the temperature of a PV cell.

As the temperature decreases, the open circuit voltage increases considerably and Vice Versa.

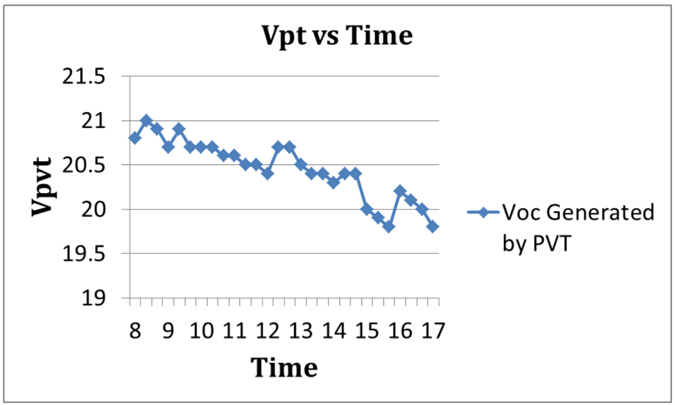

Chart 4 - Variation in Open circuit voltage induced in novel PVT collector module

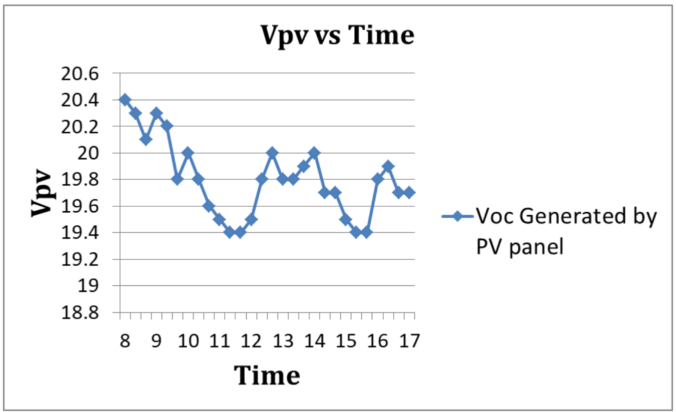

Chart 5 - Variation in Open circuit voltage induced in reference PV module

4.4 Volume flow rate effect on the thermal performance of the PVT collector

The experimental investigation carried on the novel PVT collector and reference PV panel shows that the temperature of water having 30 litre volume increases from 24°C to 45°C in 8 complete sunny hours, however there is fall in output water temperature with the increased volume flow rate. At lower volume flow rates, more heat is occupied in the small mass of water, therefore results in higher output temperature of water. Thus reduction in output temperature with the increase in the volume flow rates determines that huge mass of water accumulates higher heat but with less temperature. It is attributed to the reason of a certain amount of heat absorbed by huge mass.

5. CONCLUSIONS

The design of a water-based hybrid photovoltaic-thermal collector has been studied in this work. Since the very first step, the intention was to develop an optimum design of hybrid collector characterized by electric and thermal productivity, but also by economic reliability and feasibility, in order to reach a cost of energy lower than separated production through traditional PV and thermal solar systems, also taking advantage of material savings due to architectural integration.

A deep assessment of advancements in photovoltaic thermal techniques has been done, carefully describing the different thermal absorber technologies and their integration methods with photovoltaic components. Among the several module typologies found in literature, the best option in terms of uniform cooling of a PV panel, and optimum overall performance and cost-effectiveness has resulted in selecting the flat plate collector where photovoltaic module is hit by solar rays and is simultaneously cooled down by heat transfer fluid (Water) circulating on the rear side.. Various parameters have been considered, as like mass flow rate and its impact on electrical, thermal and overall performances.

The absorber plate has been chosen through the comparison of the best available absorber technologies, channel configuration and least expensive material use, which are already adopted for evaporators and recently introduced for hybrid solar collector. Channels shape and their arrangement has been object of careful analysis, since they affect both electrical and thermal performances. The spiral flow channel arrangement has been preferred over the remaining ones because it ensures more homogeneous temperature distributions, lower pressure drops and having higher overall efficiencies. A proper design has concerned also inlet and outlet manifolds and channel in order to minimize the presence of unequal flow distributions. Poly-crystalline technologies have been chosen for their high electric yield with respect to other technologies, due to its availability in the market. Thermal adhesives have been chosen in order to laminate PV panel and metal absorber at the current design stage.

Further, the experimental investigation has been successfully carried out. The experimental investigation concluded that the novel PVT collector module with newly designed absorber has outperformed the standalone PV module, and it gave excellent electrical and thermal results than the reference one. However, the performance can be further improved by redesigning the prototype, standard manufacturing methods.

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