A Three-Dimensional Modeling of Photovoltaic Thermal Collector

H. Ben cheikh el hocine*, K.Touafek**, F.Kerrour***, A. Khelifa****, I. Tabet*****, H, Haloui******

*Unité de Recherche Appliquée en Energie Renouvelables, URAER, Centre de Développement des Energies Renouvelables, CDER, 47133, Ghardaïa, Algeria

**Unité de Recherche Appliquée en Energie Renouvelables, URAER, Centre de Développement des Energies Renouvelables, CDER, 47133, Ghardaïa, Algeria

***Laboratoire de Modélisation des Dispositifs à Énergies Renouvelables et Nanométriques, Département d'électronique, Université frères Mentouri Constantine, 25000, Algeria.

****Unité de Recherche Appliquée en Energie Renouvelables, URAER, Centre de Développement des Energies Renouvelables, CDER, 47133, Ghardaïa, Algeria

*****Unité de Recherche Appliquée en Energie Renouvelables, URAER, Centre de Développement des Energies Renouvelables, CDER, 47133, Ghardaïa, Algeria

******Unité de Recherche Appliquée en Energie Renouvelables, URAER, Centre de Développement des Energies Renouvelables, CDER, 47133, Ghardaïa, Algeria

(bencheikh_80@yahoo.fr, khaledtouafek@yahoo.fr, f_kerrour@yahoo.fr, khelifa_karim@hotmail.fr, tabet21@yahoo.fr, haloui_h@uraer.dz)

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Abstract- In order to obtain a high current efficiency a photovoltaic generator PV, it has been necessary to recuperate the heat dissipated by combination a PV to a thermal heating system. The heat exchanger is under the PV, thus cooling the cells back face. Such a system therefore improves the efficiency of the PV module while extracting useful heat calories heating. In this paper, a 3D model of a new PVT collector has been implemented using the Comsol environment. A (FEM) approach is used for the analysis of the thermal and electrical behavior of new absorber integrated for the PVT collector which has as an advantage of a simple realization and to use a material of galvanised steel for it low cost compared to other configurations of PV/T hybrid collectors. Some results are presented the temperature of the PVT collector decreases with the increasing flow rate, For a flow rate of about 0.0016 kg/s and irradiation of 1000W/m² and ambient temperature equal to 20.15 °C, the temperature reaches a value equal to 55.96°C. The influence of mass flow rate in the PVT collector demonstrate that the PV cell temperature decreases with the increasing mass flow rate and the increases until the flow rate reaches about 0.0256 m/s; it reaches a value equal to 23.845 °C and electrical power equal to 59.434 after these values will be maintained at a relatively constants values.

Keywords PV module, photovoltaic, Photovoltaic-thermal PVT, finite element method, COMSOL.

1. Introduction

The PV cell temperature increases by the absorbed solar radiation that is not converted into electricity causing a decrease in their efficiency; for monocrystalline and amorphous silicon solar cells the efficiency decreases by about 0.45% and 0.25% for every degree rise in temperature. Recpectively, depending on the module design [1].

to create the hybrid solar collector (PVT), a PV panel is assembled with a thermal solar collector that can simultaneously produce two forms of energies (electric and thermal). These deferent energy systems were evaluated on several sides exegetic and economic [2, 3].

A major research and development work on the photovoltaic thermal (PVT) hybrid technology has been done since last 30 years. Till date many researchers have done a lot of work and numbers of studies have been carried out in designing, simulation, modeling, and testing of these systems.

The different applications of PVT on commercial level are there but it is still limited due to product reliability and cost. Important research is necessary in the area PVT predominantly in the thermal design of the absorber and manufacturing, materials and coating selection, energy conversion efficiency, cost minimization, performance tests, and control a system reliability [4]. For their applications can be cited building integrated air PVT system, solar air heating PVT system, liquid PVT collector, concentrator PVT system and heat-pipe-based PVT [5].

There are several types of PVT collectors and they are classified with respect to the fluid used, shape of the collector and whether it's integrated into a building or not. Furthermore, existence of glazing on the collector is another factor that distinguishes a PVT collector's characteristics [6].

Liquid type PVT collectors, air type PVT collectors, concentrating PVT collectors and building integrated PVT collectors are the four different types of PVT collectors [7].

Ibrahim et al. [8] have presented new absorber design for the system. Saving energy efficiency increased by 73% to 81%.

Touafek et al. A new design of the air hybrid solar collector have been manufactured and studied. It was found that it has presented better thermal and electrical. It has a thermal efficiency of 48% [9].

Li et al. have designed and tested a new static incorporated static CPC-PV/T system. The results show good agreement with the theoretical and experimental study to predict the optical efficiency under outdoor conditions. [10]

Huang et al. have studied an integrated solar-thermal system (IPVTS). The results indicate that the solar PVT collector consisting of a corrugated polycarbonate panel can obtain an approximately 61.3% yield [11].

The results of performance analysis of both single and double-pass PVT air systems in the steady-state; executed by Sopian et al. [12], show that the double-pass photovoltaic thermal solar system produces better performance than the single-pass module at a normal operational mass flow rate range.

the modeling and simulation of the performance of PVT water collector studied by Kalogirou [13], demonstrate that the mean annual efficiency of this system increases from 2.8% to 7.7% and in addition covers 49% of the hot water needs in a house, thus increasing the mean annual efficiency to 31.7%.

A photovoltaic thermal collector was bluilded by Sandnes and Rekstad. They evaluators found that the paste of solar monocrystalline silicon cells on the absorbing surface would reduce the solar energy absorbed by the module [14].

A thermal model for an integrated photovoltaic thermal solar system developed by Tiwari and Sodha was compared with the model of Huang et al. [15]. The simulations predicted a daily primary energy saving efficiency of around 58%, which was in good agreement with the experimental value (61.3%) obtained by Huang et al.

The scope of this paper is the analysis of new configuration for hybrid PVT collector based on a new integrated absorber configuration using the Comsol environment.

2. Theoretical Model

The absorber of new configuration for hybrid PVT collector is formed by two types of the first is parallel vertical tubes wherein the heat transfers fluid, and the second is an enclosure.

The performances of collector is dependent on how they are arranged, i.e., on the flow rate through risers and on the inlet temperatures to individual modules.

The design of collector modules is not the same; the performance of the prototype will not be the same. In the series arrangement, the performance of the second module will not be the same as the first as its inlet temperature will be the outlet temperature of the first. The outlet temperature of the water at the outlet of the collector in parallel vertical tubes PVT given by T_{fo1}becomes the inlet temperature to the collector whose PVT absorber is an enclosure given by T_{fi2}, $T_{fi2} = T_{fo1}$.

3. Numerical Modeling

For water flowing through the tube, the energy balance of flowing water through duct tube is given by,

$$Q_{u,1} = A_1 F_{R_1} \left\lfloor S_1 - U_{L,1}\left(T_{fi} - T_a\right)\right\rfloor \tag{1}$$

Where T_{fi} is the inlet temperature to the pair of collectors and T_{fo1} is the inlet temperature to the second collector, which is found from the outlet of the first collector:

$$T_{fo1} = T_{fi} + \frac{Q_{u,1}}{\dot{m} C_f} \tag{2}$$

In the second case

$$Q_{u,2} = A_2 F_{R_2} \left(S_2 - U_{L,2}\left(T_{fo,1} - T_a\right)\right) \tag{3}$$

where, A_1, A_2 are the collector area of first and second collector; Ta is the ambient temperature; The quantity F_R is equivalent to the effectiveness of conventional heat exchanger, which is defined as the ratio of the actual heat transfer to the maximum possible heat transfer.

$U_{L,1}$ and $U_{L,2}$ are the overall thermal loss efficient of first and second PVT collector its value may be computed by using the concept of thermal network

The value of a heat loss at the upper surface (1D model) $U_{L,1}$ and F_{R1} was calculated by, Formula of Klein (Duffie and Beckman, 1991, p. 260) [16].

The useful heat output from two combinations is given as:

$$Q_{u,1+2} = Q_{u,1} + Q_{u,2} \tag{4}$$

The thermal efficiency is given by

$$\eta_T = \frac{Q_{u,1+2}}{A_T G} \tag{5}$$

$$\eta_T = \frac{\dot{m} C_p \left(T_{fo} - T_{fi}\right)}{A_T G} \tag{6}$$

$$\eta_T = \eta_{th_0} - a_2 \frac{T_{fi} - T_a}{G} \tag{7}$$

$\dot{m}$ is mass flow rate, Cp is specific heat capacity , η_{tho} the zero loss efficiency for global radiation (G) in W/m^2 at normal incidence, T_a is the ambient temperature, , and a_2 terms that describe the temperature-dependent heat losses.

The electrical efficiency of a PV module represented by formulate of Schott [18] is given by:

$$\eta_e = \eta_0 \left(1 - 0.0045\left(T_c - T_{ref}\right)\right) \tag{8}$$

As is shown in the Eqt (8). η_0 is the reference efficiency of the solar cell at T_{ref} =20°C which is in our study 15%.

4. Analysis Using Comsol

The Finite Element Method is the numerical technique applied by COMSOL for finding approximate solutions to boundary value problems.

The three dimensional geometry of the new configuration of PVT collector (shown in Fig. 1) developed in COMSOL was used simulations.

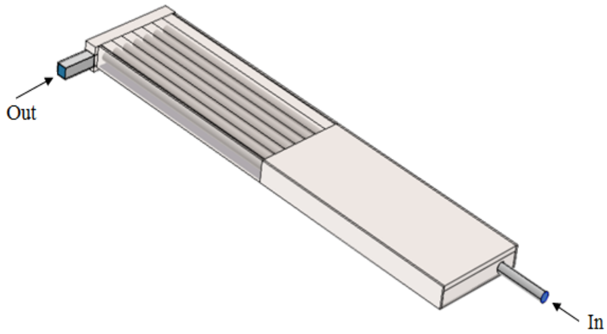

Fig. 1. Three dimensional view of the geometry used in COMSOL.

This section proposes the simulation steps for the thermal analysis of the proposed model. For each analysis, a brief summarization of the specific parameters and boundary settings is presented. The thermal analysis has been developed using the Comsol's Conjugate heat transfer module.

In the Conjugate Heat Transfer Module, the following conditions were manually added to the model:

- *Heat Transfer in Solids*

The collector consists of an assembly of elements which are: The transparent cover, amonocristallin's photovoltaic module, absorber, the insulation ensured by glass wool.

- *Fluid*

COMSOL numerically solves the continuity and momentum equations, which are the governing equations for the fluid flow, and are shown below in equation (9) and equation (10), respectively.

$$\nabla(\rho u) = 0 \tag{9}$$

$$\rho u.\nabla u = -\nabla p + \nabla.\left(\mu\left(\nabla u + (\nabla u)^T\right)\right) \tag{10}$$

The conduction-convection equation is also solved for the heat transfer in the flowing water, which is shown in Equation (11).

$$\rho C_p u.\nabla T = \nabla.(k \nabla T) \tag{11}$$

T (K) is fluid temperature, C_p (J/kg·K) is the specific heat at constant pressure, ρ (kg/m^3) is the fluid density, u is the flow velocity (m/s), k (W/m·K) is the thermal conductivity.

- *Temperature*

$$T = T_0 \tag{12}$$

- *Outlet*

Outlet (Water flow exit, set to pressure, pressure = [1atm]);

- *Heat Flux 1*

The heat flux (thermal flux) is the rate of heat energy transfer through a unit of area in a given surface. The following equation was used in the heat flux interface in COMSOL:

$$-n.\left(-k\nabla T\right)=q_0 \qquad (13)$$

The term q_0, which corresponds to the incoming flux, is set up equal to 1000W/m^2;

- *Heat Flux 2*

Is the convective contribution to the total flux, depends by the heat transfer coefficient h and the difference between the external temperature T_{ext}, and the unknown temperature.

$$-n.\left(-k\nabla T\right)=h.\left(T_{ext}-T\right) \qquad (14)$$

The value of the initial external temperature has been set up equal to 293.15 K while the *h* value has been computed equal to 17,8 W/m^{2}K.

- *Surface-to-Ambient Radiation 1*

Is the radiative contribution to the total flux on the collector.

$$-n.\left(-k\nabla T\right)=\varepsilon\sigma.\left(T_{amb}^4-T^4\right) \qquad (15)$$

σ is the Stefan-Boltzmann constant, *ε* emissivity, and the T_{amb} represents the environment temperature.

The material used for both the absorber plate and the tube is copper; the input parameters used in the analysis are shown in Table I.

Table 1. Data used for simulation

Layer	λ(W/m.K)	C(J/Kg)	Rho(kg/m^3)	Value
Glass Cover	1	480	2500	0.8
PV Cell	131	700	2330	0.8
Layer of Tedlar	0.035	560	1200	/
Absorber Plat (Steel)	65	400	7800	/
Insulation	0.035	1000	1.127	0.1

- *Meshing*

The simulations required good refinement of the finite elements in the mesh to acquire acceptable results.

The collector was meshed in COMSOL using the built-in physics controlled mesh sequence setting. As shown in Fig. 2 below, the number of mesh elements increase at each boundary so that the heat transfer and flow fields can be resolved accurately, while ensuring that accurate results.

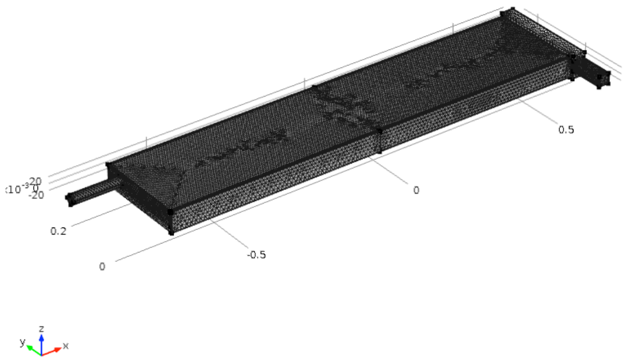

Fig. 2. Three dimensional view of the mesh used.

5. Experimental Study

A. Materials Used

- Monocrystalline silicon for photovoltaic module.
- Galvanized steel tubes 12/17 Ø
- Galvanized steel tube 20/27 Ø
- Two sheets of galvanized steel [1mm-3mm]
- 20mm angle iron
- 30mm aluminum angle
- Polystyrene
- Glass wool
- Paintings (black and white).

6. Results and Discussion

The new hybrid PVT collector placed on the control structure Fig. 3. this photo taken in the laboratory of the Unit for Applied Research in Renewable Energy in Ghardaïa. Data acquisition of type 34970 (Data Acquisition/Switch Unit) is used to determine the values of temperature. Two K-type thermocouples are placed at two different points T_{av1} and T_{av2} to the front panel to confirm uniform distribution temperature on the front and a thermocouple placed on the rear panel to identify the assurance of perfect isolation.

Fig. 3. Photo of the new PVT collector

Calculations are done for typical day of November 2/11/2015 in the site of Ghardaïa; for a given design and climatic parameters. The variations of global solar radiation and ambient temperature for a typical day in the month of November 2015 of Ghardaïa site is shown in Fig. 4. The measure of solar intensity and ambient temperature are carried every two minutes in order to obtain a good accuracy for all measurements performed as temperature at different location.

The experimental results are presented from following figure, we noted that variation of front face temperature of the collector was measured, it maximum value reached to 53,646°C. The outlet temperature of the fluid equal to 43,282°C, the maximum difference between inlet and outlet temperature of fluid equal to 14.246°C observed at 12.29h which shows the gain in produced thermal energy for a ambient temperature equal to 22.86°C.

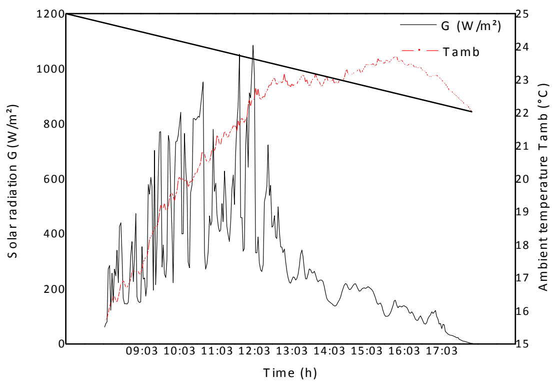

Fig. 4. Hourly variation of solar intensity and ambient temperature for the day of 2/11/2015

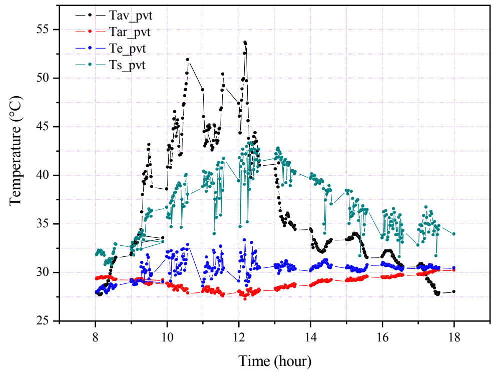

Fig. 5. Experiment values of temperatures for each component of PVT for 2/11/2015

A simulation with Matlab [17],was performed to predict the thermal efficiency of various PVT-panels. Fig. 6 show thermal efficiency variations at different PVT configurations, these results are referred to thermal efficiency of water η_{th} in the mode of water heat exchanger; the ration $\Delta T/G$ (C°W^{-1}m²) is the reduced temperature, with $\Delta T = T_i - T_a$(K). The PV/T collector in PVT with absorber in parallel vertical tubes is obviously performing more at zero reduced temperature; it was found to be 41.86% and 30% at PVT in enclosure which represents a lower value.

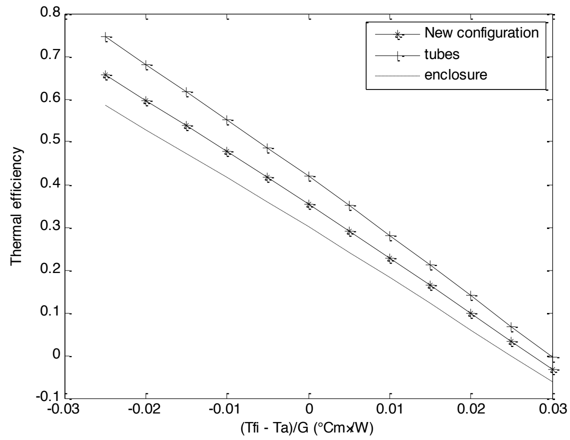

Fig. 6. Variations of the thermal efficiency according to the reduced temperature (T_{fi} - T_a)/G at various PVT-panels.

A new of design combined PV-thermal collector has been evaluated in software-COMSOL MULTIPHYSICS, to investigate the thermal performance, it structure is obtained through the superposition of more layers cited above. Fig.8 illustrates 3 dimensional plots for the steady state solution of temperature profile of PVT. The first step of simulation performed assume that the water inlet temperature was of uniform temperature equal to 293.15K (20°C), which is the same temperature specified for the ambient temperature and working fluid flow rate equal at 0.0016 kg/s presnted in Fig. 7.

The Fig. 9 shows the temperature distribution in new design of absorber for value of the wind speed equal to 1 m/s; the value of radiation 1000W/m^2, an ambient temperature of 293.15K (20°C), it found equal to 53.89°C.

The electrical energy of the PV Cell is presented in Fig.10. It can be observed that the electrical energy is linear function of module temperature. The electrical energy of PV module declines with the increase in temperature of the PV module, for a cell temperature equal to 25°C and reference temperature equal to 20°C the electricl power equal to 59 W.

Numerical simulation (CFD) can conduct a parametric sweep aims to clarify and quantify the evolution of various parameters such as temperature profile and electrical power depending on same parameters meteorological and physical (Irradiation G, mass flow rate) involved in the study of the performance of our model.

The mass flow rate range is (0.0001 - 0.04) m/s with a step of 0.0015 m/s. It influence in term of the temperature and electrical power of collector PVT is presented in Fig.11 and Fig.12. The temperature of the PV cell decreases with the increasing mass flow rate until the flow rate reaches about 0.0256 m/s; it reaches a value equal to 23.845 °C after which it maintains at a relatively constant value.

When the mass flow rate increases beyond 0.0256 m/s, the electrical efficiency of the novel design of collector will be maintained at a relatively constant level 59.434 W, as shown in Fig.12. Explain that heat extracted by the cooling fluid has reached a saturated level and it cannot be increased further by increasing the mass flow rate.

From the presented results of Fig. 13, it can be seen that the temperature and electrical power of PVT collector increases when the solar radiation increases, for example, for an illumination of 600W/m^2, and ambient temperature equal to 293.15K for, the collector temperature reaches a maximum value equal to 41.72°C, for flow rate equal to 0.0016 kg/s, keeping the other constant values.

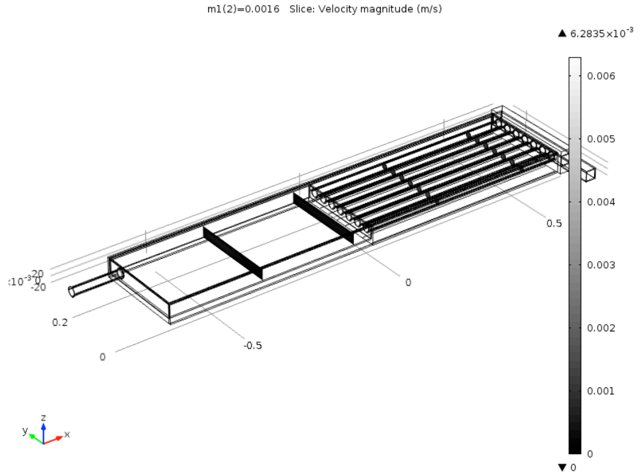

Fig.7. Velocity in the PVT collector

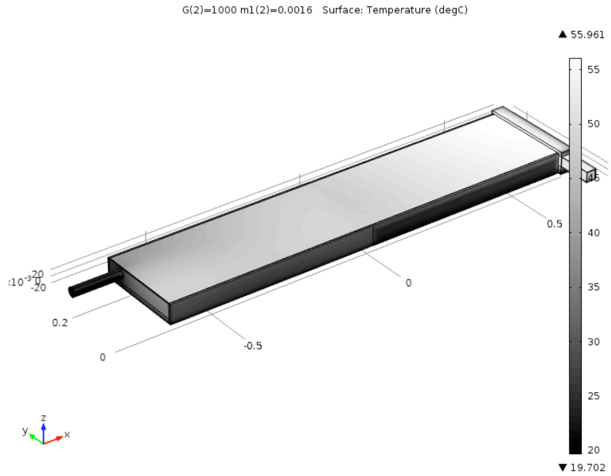

Fig. 8. Temperature variation in the PVT collector

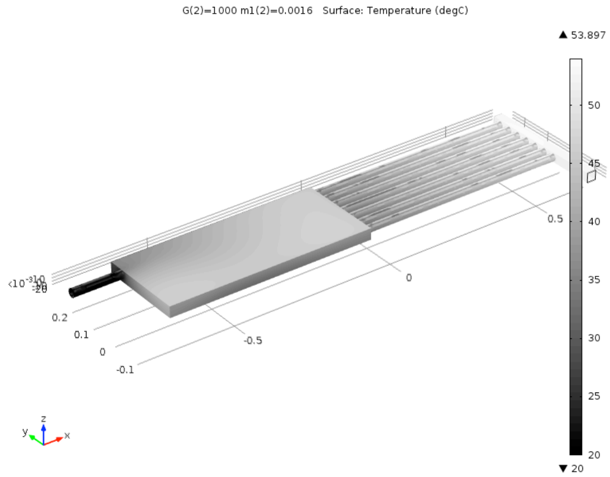

Fig. 9. Temperature variation in new design of absorber.

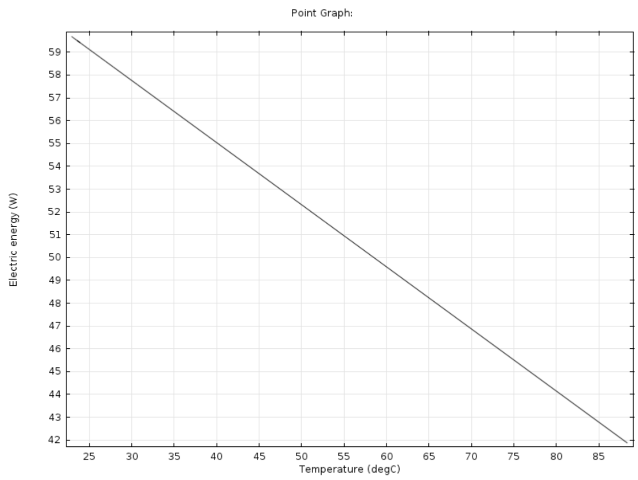

Fig.10. Electrical power as a function of PV cell temperature

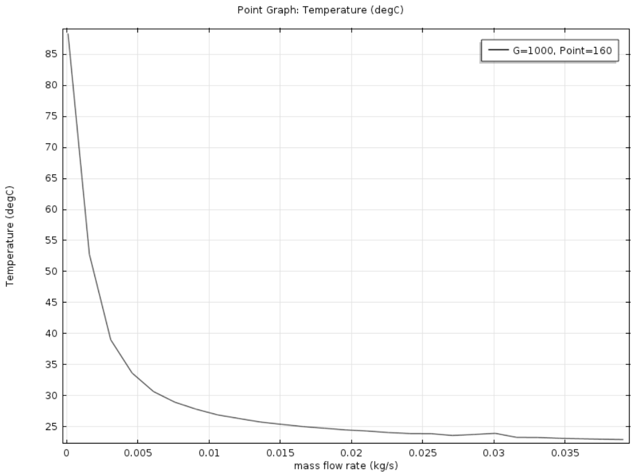

Fig.11. Influence of flow rate on the cell temperature of PVT.

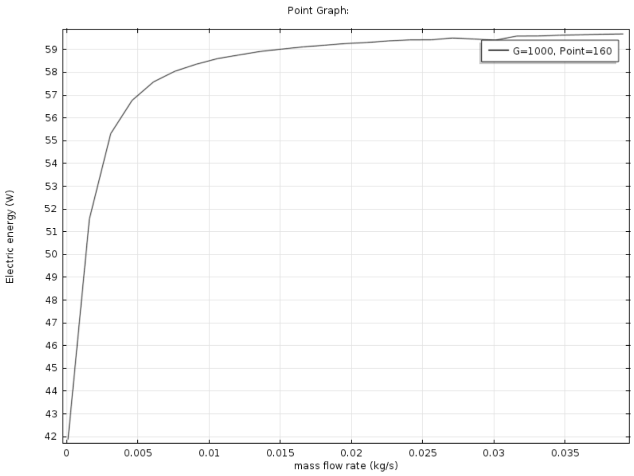

Fig.12. Electrical energy as a function of flow rate in the new PVT collector

A B

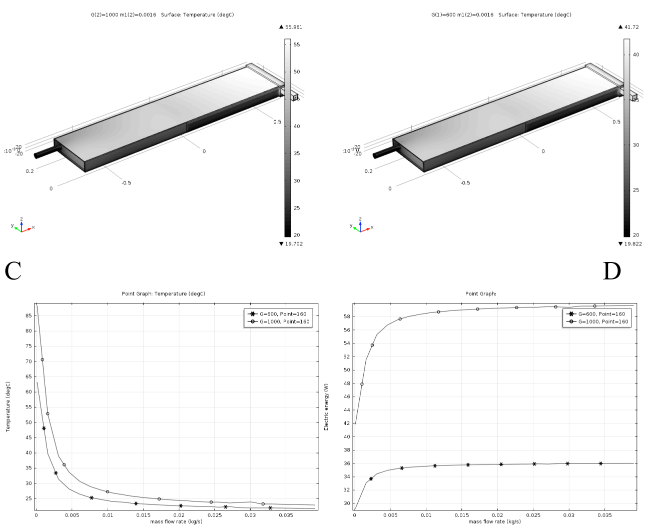

Fig. 13. Influence of solar radiation and on the temperature and electrical power of PVT collector.

7. Conclusion

We have presented the new configuration of hybrid collector (parallel vertical tubes - an enclosure). The aim is to increase the energy effectiveness of electric and thermal conversion with the lowest cost compared to the already existing conventional hybrid collector.

Some results of this configuration has been presented; these clearly show the direct impact of various parameters, in particular the solar radiation and mass flow rate on the thermal and electrical parformances of the collector.

the simulate results could be indicated that having a higher mass flow rate results in higher power production from PV Cell due to decreased its temperature, assists in keeping the PV Cell temperature at optimum value. The operating temperature of cell could be maintained at 23.84 °C and the electrical energy could also be kept at around 59.43 W. The mass flow rate of 0.0256 kg/s is sufficient to absorb the maximum amount of heat from the PV cell. When the mass flow rate exceeds this value, the electrical energy is no longer affected. The integrated system could produce useful power augmenting power production from PV cell.

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