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Research Article

Performance Enhancement of a Water Cooled BIPV System

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Abstract

Building-integrated photovoltaic systems (BIPV) currently represent a fundamental concept for the realization of sustainable buildings. However, these systems like any photovoltaic device are endowed with a limited efficiency due to the negative effect of the rise in the temperature of the cells. To limit this inconvenience, a cooling system must be applied. In this study, a suitable geometry was considered based on the temperature distribution in the base system. Indeed, a particular cooling system with a contact surface and a volume of water which increase as the temperature of the photovoltaic cells increases is considered. In addition, the external heat exchange surface of the proposed system is varied, linear and cylindrical based surfaces are studied. Numerical simulations were performed using the CFD package, Ansys. The main attention was focused on the overall system's temperature and electrical efficiency improvement. Moreover, the gain generated in thermal energy is evaluated. The results revealed that the proposed system allows an important reduction of the PV cell temperature. While the non-cooled BIPV system temperature variation was in the range of 312.5 K - 348.5 K for a solar radiation ranging from 200 W/m^2 to 1000 W/m^2, this variation is reduced to small values for the water cooled system, respectively from 301 K to 310.5 K. This reduction in the temperature of the PV cells has directly resulted in an improvement in the photovoltaic efficiency of the system where a minimum average value of 15% has been noted, while the values noted for the uncooled system vary between 12.3% and 14.8% in depending on the incident radiation. Concerning the effect of the external heat exchange surface, the effect was not remarkable on the electrical performance of the system, however, the linear surface-based system proved to be more efficient in terms of thermal production than the cylindrical one. Finally, the effect of the flow rate is also discussed and the results show that for a relatively high value like 0.22 kg/s, a good reduction in the temperature of the PV cells can be achieved while ensuring a significant thermal production.

Keywords: BIPV; adapted geometry; Computational Fluid Dynamics (CFD); performance improvement

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Introduction

Nowadays, reducing energy consumption is one of the major issues in reducing the environmental impacts associated with the building sector. That is why; the energy policies of the countries are undergoing great changes and the building sector is at the heart of these demands imposed by the modern way of life [1, 2]. Different governments [3, 4] and [5] have changed their energy strategies and have moved towards more efficient buildings. They also sought to use efficient solutions to achieve low energy buildings [6-8]. Photovoltaic (PV) systems represent one of the most promising technologies that meet building energy regulations while pleasing environmental requirements [9]. With the increase in the use of photovoltaic systems integrated into buildings (BIPV), increasing their efficiency is essential since the large part of the incident solar radiation is used to raise the temperature of the cells, thereby causing a braking of the photovoltaic conversion. Moreover, it has been shown that each degree of increase in the temperature of the cell implies a reduction of 0.4 to 0.65% of the electrical efficiency of the cell [10]. To overcome this problem, different cooling systems have been designed. These resulting devices called Building Integrated Photovoltaic Thermal BIPV/T generate both an improvement in the electrical power of the PV system and additional useful thermal energy which can be recovered by the heat transfer fluid and used in other applications such as air heating or water production domestic hot water [11]. It was around the 2000s that the BIPV/T system became popular, with the development of zero net construction and encouragement for the exploitation of solar energy. In addition, the researchers focused on these BIPV systems integrated into the building envelope, whether through the exterior walls or the roof. These systems consist of two skins, the PV panel and the outer skin of the building, separated by an air space. They allow the passage of fresh air through the air gap and the extraction of heat from the PV modules. The heated air is either released to the environment or used to meet thermal energy needs. The airflow in a vertical channel heated by the PV components was studied experimentally and numerically by Hanessian et al. [12], who showed that the velocity increases with heat flow and discussed different outlet size and design parameters. Mei et al. [13] studied, using TRNSYS simulations, a dynamic thermal model of a ventilated PV façade/solar collector system. They discussed the effect of facade location and ventilation on heating and cooling loads. Similarly, Zogou and Stapountzis et al. [14] were also based on TRNSYS simulations to numerically examine the performance of a south-ventilated PV façade and discuss the effect of the fan capacity on the overall heat transfer. In this same axis, different mounting parameters were studied by Yun et al. [15] who have shown that the suitable choice of the position of the air gap outlet allows for the correct operation of a ventilated PV façade. Wilson and Paul [16] used ANSYS which is based on a Finite Volume Method to discuss the effect of the air gap under a PV panel and the inclination angle on electrical efficiency of a photovoltaic panel under natural and mixed convection conditions. They showed that for the natural convection case, an angle of 90° allows the best efficiency which is in the range of 10.75% to 10.92%, while for the mixed convection condition, a maximum efficiency 11.98% can be achieved for a velocity of 3 m/s. This simulation tool was also used by Gan [17, 18] who studied the effect of air gap's size on the PV system performance. They found that the mean and maximum PV temperatures decrease with the increase in pitch angle and air gap. They also concluded that for multiple module installation, the air gap should be between 0.12 m and 0.15 m air gap, and for single module installation, this value must be between 0.14 m and 0.16. In another numerical investigation, Assoa et al. [19] were interested to the effect of the air gap ventilation type (natural and forced ventilation) on the system's thermal and electrical performance and showed that the forced ventilation allows the highest thermal production. A BIPV system with natural ventilation was studied by Agathokleous et al. [20, 21] who proved that natural ventilation of their system could considerably decrease its PV temperature and then improve its overall efficiency. The improvement of air based BIPV performance was the research axis of different authors like Sopian et al. [22] who proposed the use of a double pass system producing more heat and electrical energy. Other alternative was proposed by Rounis et al. [23] and Yang et al. [24] who developed different improved designs of open loop air-based BIPV/T systems with two inlets and evaluated the resulting improvement relatively to the single-inlet system. The use of phase change materials PCM in ventilated BIPV façade was proposed by Kant et al. [25] who tested various design parameters like the PV panel height, the air gap, the mass flow rate and the PCM thickness and showed that their optimum values are respectively 3 m, 0.02 m, 0.18 kg/s and 0.04 m for maximizing the PV power production and 3 m, 0.08 m, 0.091 kg/s and 0 m for maximizing the energy extracted by the air. Similarly, Laura Aelenei et al. [26] integrated these materials in their BIPV system and studied its performance under natural convection and in climatic conditions of Bratislava. They showed that this change allowed a reduction of 20°C in the PV temperature, resulting in an improvement of about 10% and 20% in the system's thermal and overall performance, respectively. Despite the resulting improvements in the use of PCMs, they have shown limited effectiveness due to their low thermal conductivity. This drawback was overcome by different techniques like the use of fins [27-28], highly conductive composite material [29, 30], and capsules [31] for the heat transfer surface extension. Similarly, Hussain et al. [32] studied an experimental design of a PV system with a hexagonal honeycomb heat exchanger located under the PV module. It was concluded that the honeycomb can enhance the thermal efficiency of the PV panel which reached 87% at a mass flow rate of 0.11 Kg/s while that of the system without honeycomb didn't exceed 27%. The most popular solution evaluated for improving the performance of PV systems is cell cooling. So various cooling methods were proposed by different authors like Bayrak et al. [33] who built experimental devices of cooled photovoltaic (PV) panels. They found that a PV system with fin produced the highest power generation with a value of 47.88 W while that corresponding to a PV with PCM is only of of 44.26 W. Similarly, cooled PV system performance can be improved by the use of multiple inlets [34, 35] or double pass [36] configurations.

So different techniques were investigated for PV systems electrical performance improvement. Concerning the proposed cooling techniques, all the tested designs are based on simple configurations which uniformly cover the whole cell surface. In the present work, we were based on the temperature distribution in the photovoltaic cells which is cold at the entry level (at the bottom) and rises as we approach the exit (top). Therefore, we have opted for cooling configurations that adapt perfectly to this temperature distribution and we have discussed some geometric parameters in order to assess the most suitable design that improves the performance of PV cells with the minimum cost and weight on the BIPV system.

Computational fluid dynamics simulation set up

System description and meshing

In this numerical contribution, we were based on the experimental system experimentally tested by Agathokleous & Kalogirou [21]. The considered configuration is a façade vertical application of a BIPV system with two opening area left at the top and the bottom sides of the domain. It consists of four successive layers, namely, the PV panel, the air gap, the plexiglass sides and the wooden wall as shown in Fig.1. Their dimensions are respectively 1642*992*4 mm, 1642*992*100 mm, 1642*20*100 mm and 1642*992*200 mm.

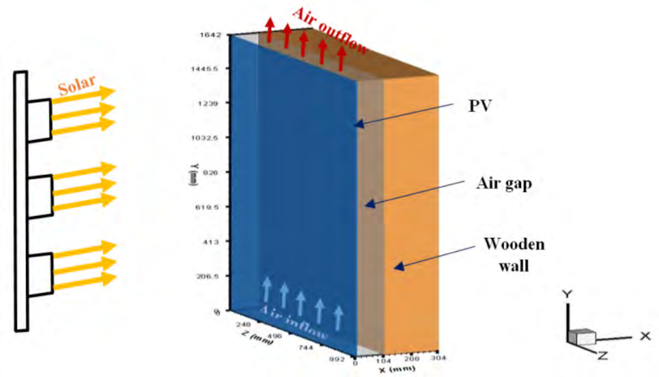

Figure 1: Schematic description of the ventilated BIPV system.

A mesh is the spatial discretization of the medium and the quality of a solution strongly depends on the shape and the number of elements involved. For the considered BIPV system, a hexahedral meshing was considered and its number, which is of 1651200, was chosen after a mesh sensibility test. The different system component's meshing is presented in Fig. 2.

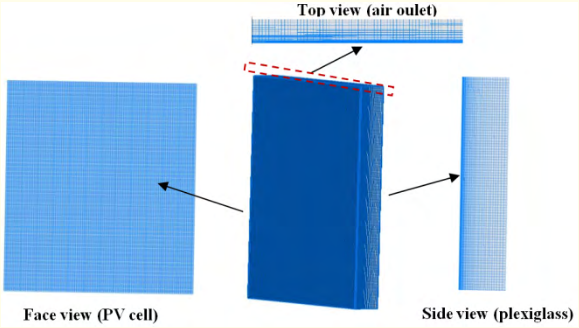

Figure 2: Generated mesh description for different viewpoints.

Assumptions and boundary conditions

For the BIPV system modeling, some assumptions were considered:

- The incident solar radiation is assumed to be perpendicular to the PV surface.
- All the materials and fluids thermos-physical properties are assumed to be constant except the air for which we considered the Boussinesq approach to model the density variation with temperature. The corresponding equation is given as follows: $(\rho - \rho_0) = -\rho_0\beta(T - T_0)$ Where ρ_0 is the air density at the ambient temperature T_0, and β is the thermal expansion coefficient.
- All the fluids and materials properties are initially considered at the ambient temperature 300 K.

The choice of the boundary conditions to attribute for each one of the fluids and materials was done according to the experimental testing process. Prescribed "pressure inlet" with a constant ambient temperature is so assigned to the air inlet while "pressure outlet" is selected at the outlet. Adiabatic boundary condition is considered for the lateral wooden and plexiglass walls. For the PV panel, the mixed condition is used which order to involve both convective and radiative heat transfers at this surface.

Numerical modeling

Fluent is one of the two computational fluid dynamics (CFD) packages included with the ANSYS computational mechanical software suite. It uses a Green-Gauss Finite Volume Method with a CellCentered formulation for the Navier-Stokes equations resolution.

For the closure of the considered equations, The RNG k-epsilon model is used and showed good results for the considered problem modeling [37]. The RNG-based K-ε turbulence model is derived from the instantaneous Navier-Stokes equations, using a particular mathematical technique which is the "renormalization group'' (RNG) method. The analytical derivation results in a model with constants different from those in the standard K-ε model, and additional terms and functions in the transport equations for K and ε. The RNG K-ε model is considered more accurate and reliable for a wider class of flows than the standard K-ε model as it has an additional term in its ε equation that significantly improves the accuracy for rapidly strained flows and its theory provides an analytical formula for turbulent Prandtl numbers.

Regarding the radiation modeling, the DO radiation model is chosen. This model allows solving the radiative transfer equation for a finite number of discrete solid [38]. It spans the entire range of optical thicknesses, allowing so to solve problems ranging from surface-to-surface radiation to extended problems. It allows also the solution of radiation at semi-transparent walls and presents moderate computational cost and modest memory requirements for typical angular discretizations.

Moreover, the pressure-based solver was used and the SIMPLE algorithm was considered for coupling pressure and velocity. The convection, turbulent and diffusion radiation terms were discretized based on the second order upwind scheme while the PRESTO scheme was considered for the pressure. A convergence criterion of 10^{-5} was chosen for the continuity, momentum, k-ε and DO equations and a value of 10^{-6} was selected for the energy equation.

CFD model validation

For the CFD model validation, the numerical results are compared to the experimental data of Agathokleous and Kalogirou [21] for a typical ventilated BIPV system. The experiments were carried out for 160 min and test were considered for a constant radiation of 800 W/m^2. Fig. 3 presents a comparison of CFD results and experimental data of Agathokleous and Kalogirou [21]. The monitored parameters are the PV temperature and the air temperature and velocity. For the temperature of the PV and air, two locations were considered for the comparison (bottom and top sides) while for the air velocity, results were only examined in the middle of this gap, exactly as presented in experiments. A good agreement between simulations results and experimental measurements is shown and that for all the tested parameters. We noted a similar evolution between the simulation and experiment and that the average deviation does not exceed 10% for all these parameters. In conclusion, the proposed three dimensional model is accurate enough to perform a parametric study and discuss the effect of some parameters on the BIPV system performance.

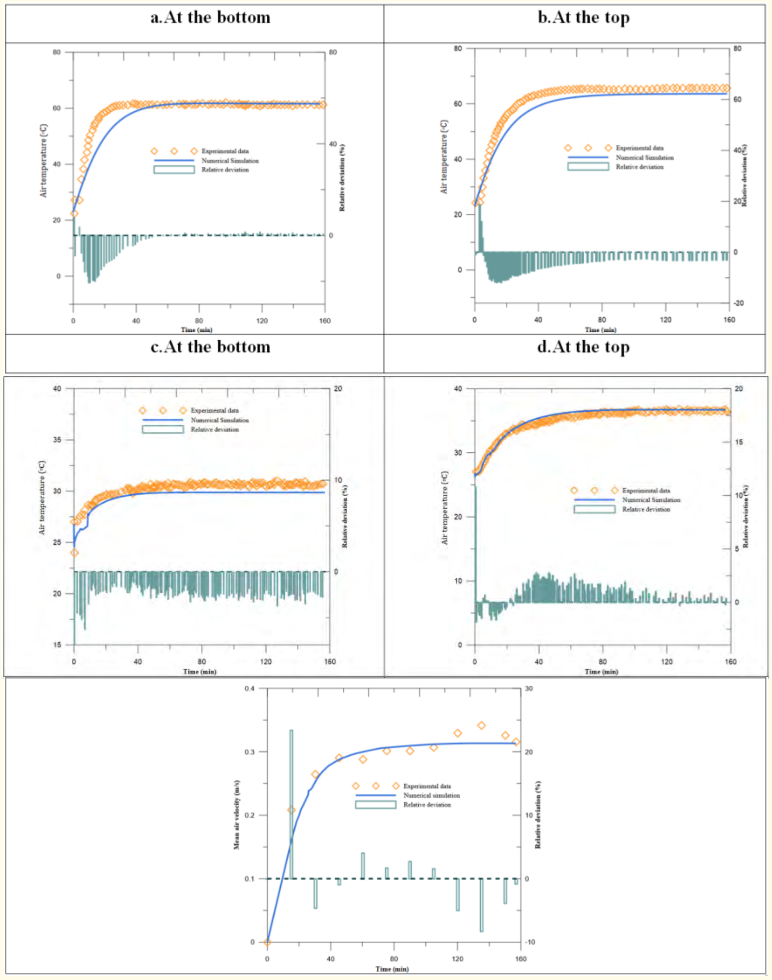

Figure 3: Results of the CFD model validation.

BIPV system performance improvement

In this numerical investigation, we were based on the temperature distribution results presented in Fig. 4. a. As can be seen, this distribution is characterized by cold zones at the inlet which gradually heat up as we draw near the outlet. For this system' performance optimization and more particularly to ensure an adequate cooling structure of the PV cell, we have considered a structure specially adapted for this purpose. Indeed, we have opted for a device with a small inlet section and an exchange surface which widens in the direction of the flow as shown in fig. 5. a. This shape allows to extract more heat from the photovoltaic cells, to have a more uniform temperature distribution and less significant differences, which promotes a better electrical production. On the other hand, and in order to avoid any constraint relating to the weight, various configurations which differ by the level of the first full contact between the cooling system and the PV cell (the distance L). The distance L was varied from 0.1 m to 1.6 m with a step of 0.3 m. The choice of the optimal design was based on the PV temperature presented in Figures 4. b and 4. c for L= 0.4 m and L= 1.6 m, respectively. Analysis of this contours shows that considering a full contact between the solar cell and the cooling system at the distance L=0.4 m is the most suitable for this solar system as below this value, the PV cell is relatively cold and the application of the cooling system in this area will not be technically and economically profitable.

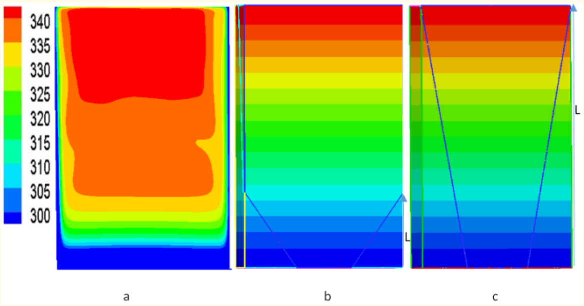

Figure 4: Temperature contours for the BIPV system.

Similarly, the nature of the external surface of heat exchange with air, linear (Fig 5.b) and cylindrical (Fig 5.c), were studied and the most advantageous system was evaluated. For this parametric study, an hexaedrical structured mesh was generated for all the studied systems and the same modeling procedure as that used for the CFD model validation was considered. The cooling structure is placed in contact with the PV cell and the cooling fluid used is the water. The modified system analysis is based on its solar cell temperature and electrical efficiency, in addition to the thermal production. The PV cell temperature is presented in Fig 6 for different solar radiation. The analysis of this figure shows that the proposed cooling systems allow an important reduction of the solar cell temperature. Indeed, for the base system, this temperature variation is in the rage of 312.5 K - 348.5 K for a solar radiation ranging from 200 W/m^2 to 1000 W/m^2. By application of the proposed cooling system, this variation is reduced to small values, respectively from 301 K to 310.5 K. This shows the effectiveness of this geometric change which proves to be suitable for reducing the temperature of the photovoltaic cells, whatever the shape of the exchange surface with the air which did not present a great effect on this parameter.

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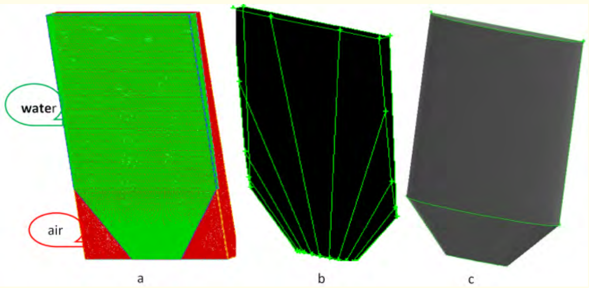

Figure 5: Modified BIPV system designs.

Similarly, this considerable reduction in temperature proves to have a positive effect on the electrical efficiency of the system, which is significantly improved. This effect is shown in Fig 7 which reveals that the electrical efficiency is increased from an average value ranging from 14.8% to 12.3% for an incident solar radiation variation from 200 W/m^2 to 1000 W/m^2 to a mean value switching between 15.8% and 15.1%. A stability in terms of electrical efficiency is thus obtained for the two considered surfaces of the modified systems, with a minimum value higher than 15%. This effect is also beneficial on the overall behavior of the entire system as well as its lifetime.

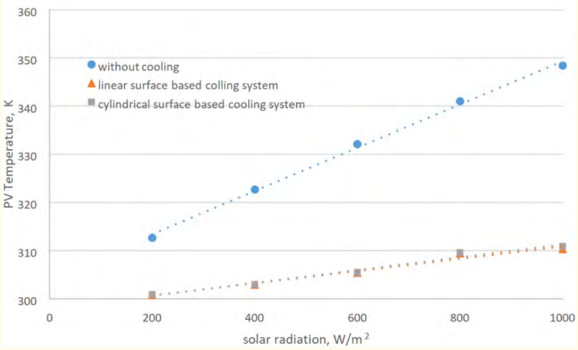

Figure 6: PV temperature at different solar radiation.

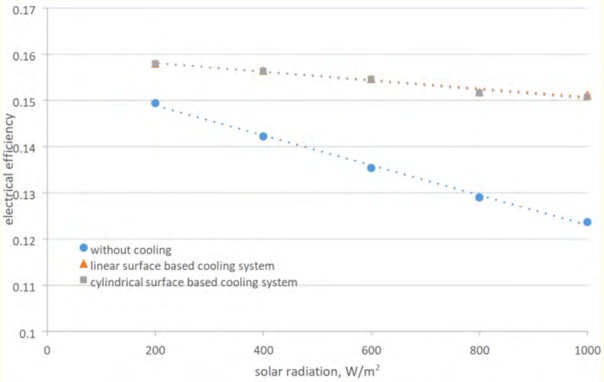

Figure 7: Effect of the proposed cooling system on the BIPV electrical efficiency.

In addition to the electrical performance considerations, an important thermal production is generated. Results of the water temperature ae presented in Fig 8 which shows a variation for the cylindrical surface based system from 300 K to 318 k for an incident solar radiation radiation ranging from 200 W/m^2 to 1000 W/m^2 while it achieves 319.5 K at 1000 W/m^2 for the linear surface based system.

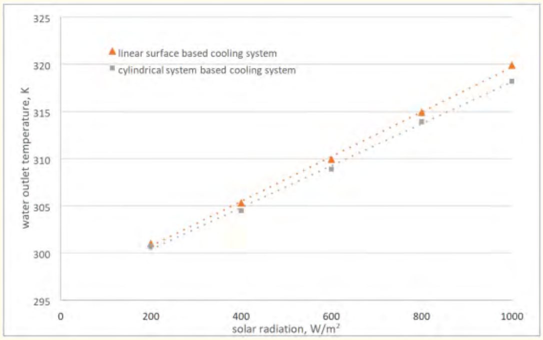

Figure 8: Thermal production of the proposed water cooled BIPV systems.

The thermal efficiency of the water cooled BIPV systems is presented in Fig 9 which shows, for the cylindrical heat exchange surface, a variation from 12% to 15.1% when the solar radiation changes from 200 W/m^2 to 1000 W/m^2 while that corresponding to the linear surface based system achieves 69.6% at 1000 W/m^2, and this is due to its higher heat exchange surface.

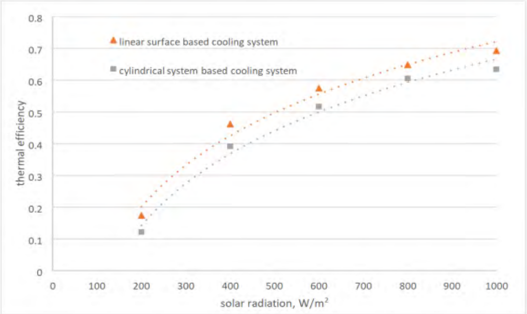

Figure 9: Thermal efficiency of the proposed water cooled BIPV systems.

The temperature evolution with the water mass flow is presented in Fig 10 for the linear surface based system, which presented the best global performance. Results clearly show a decreasing evolution as the flow increases. For a relative variation from 0.013 kg/s to 0.22 kg/s, a decrease from 319.5 K to 315.8 K was noticed for the water while the diminution corresponding to the PV cell is from 310.3 K to 304.4 K. So, as the main objective of a cooling system is the PV cell temperature reduction, high flow rates are preferred due to their positive effect on the global system electrical performance, in addition to their considerable thermal production.

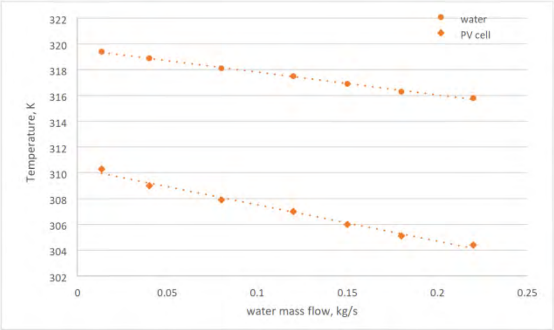

Figure 10: PV and water' temperature variation with mass flow.

Conclusions

A BIPV module with a suitable geometry of the cooling system was numerically investigated to control the module temperature and consequently to enhance the PV module electrical performance. The proposed system was chosen based on the PV cell temperature distribution which increases as we move towards the exit. A particular structure with a variable contact surface with the PV cell and a volume of water which increases as the temperature of the photovoltaic cells increases is considered. Similarly, two systems with respectively linear and cylindrical based external surface are studied. The performance of the modified systems was compared to the reference one without cooling system, where a reasonable agreement was achieved. Results clearly show that the proposed system perfectly meets the objectives targeted by this modification as it has allowed a significant reduction in the temperature of the photovoltaic cells, and this has resulted in a considerable increase in the electrical efficiency of the whole system. Similarly, the proposed system allowed an important thermal production. To conclude, a linear surface-based cooling system, with full contact with the cell starting from a distance of 0.4 m from the inlet and operating with a flow rate of 0.22 kg/s allows both to maintain an acceptable level of cell temperature and ensures an average photovoltaic yield greater than 15% with significant thermal production.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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