PV / T SOLAR COLLECTOR COMBINED WITH A HEATING/COOLING SYSTEM FOR DOMESTIC USE UNDER ALGERIAN CLIMATIC CONDITIONS: A CASE STUDY IN JIJEL

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In this paper, a hybrid photovoltaic-thermal (PV/T) solar collector with water as the primary working fluid, and a vapor compression cooling cycle with R134a as the cooling layout in a combined heating-cooling solar system has been designed and simulated, and its performances have been evaluated. Moreover, Jijel (North-East) of Algeria was taken as a case study. The obtained results show that raising the required cooling power from 0 to 200 kW at a given solar intensity improves the cooling and heating efficiencies up to 45.69 % and 22.46 % respectively. Furthermore, it has been found that increasing the mass flow rate of heating media (water) from 0 to 10 kg/s raises the solar heating efficiency from 21.78 to 53.18 %. Moreover, the obtained results revealed that solar heating and cooling efficiencies have been enhanced from 2 to 66.11 % for the standard system, and from 2.15 to 71.24 % for the modified system when solar radiation increased. On the other hand, for a typical day of May 2017, the study examined the system's performances under the meteorological conditions of Jijel, Algeria. The system achieves maximum solar heating and cooling efficiencies of 38.93 % and 41.94 %, respectively, while the overall PV/T efficiency reaches a maximum value of 80.2 % at midday.

Keywords: Hybrid photovoltaic/thermal (PV/T), Vapor compression, solar heating efficiency, solar cooling efficiency.

1. Introduction

According to studies [1-3], hybrid PV/T systems give better overall efficiencies and increased working parameters compared to conventional one. Thus, many works have been published in the literature to study these systems. For example, Shen et al [4] and Kazem et al [5], have evaluated the effect of the circulation channels design of the working fluid. Recently, several researchers have investigated the integration of PV/T systems in the field of refrigeration and/or air conditioning, and according to Lazzarin and Noro [6], coupling of PV/T with a heat pump not only makes it possible to cool the PV module and increase its electrical efficiency, but also enhance the performances of the whole system. These studies aimed to optimize some operating parameters of the PV/T system

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coupled to the refrigeration / heating system, among them: Farshchimonfared et al [7], Gao et al [8], Sarbu and Adam [9] and Mi et al [10]. Studying the performances of a combined solar cooling/heating system using a photovoltaic thermal collector (PV/T) was considered by Zarei et al [11]. In order to predict energy and dynamic exchanges, refrigerant-based photovoltaic / thermal heat pump water heaters were simulated by Tsai [12]. While Yao et al [13] have developed a mathematical model of a vapor injection heat pump system using a PV/T panel / evaporator. However, there is still a lack in researches to design and to simulate the performances of this system. Thus, in the present paper, a new layout of PV/T system has been designed for cooling and heating applications in buildings, and the climatic conditions of Jijel (North-east of Algeria) have been considered. In this system, the generated power by the PV/T solar field is used to drive the compressor, the pump and the electric heater, while the useful heat from the working fluid (water in this case) feeds the cooling and heating cycles.

2. Methodology

2.1. Description of the system

The Fig.1 shows the combined system based on a hybrid photovoltaic/thermal PV/T system with a vapor compression refrigeration system for residential cooling or heating.

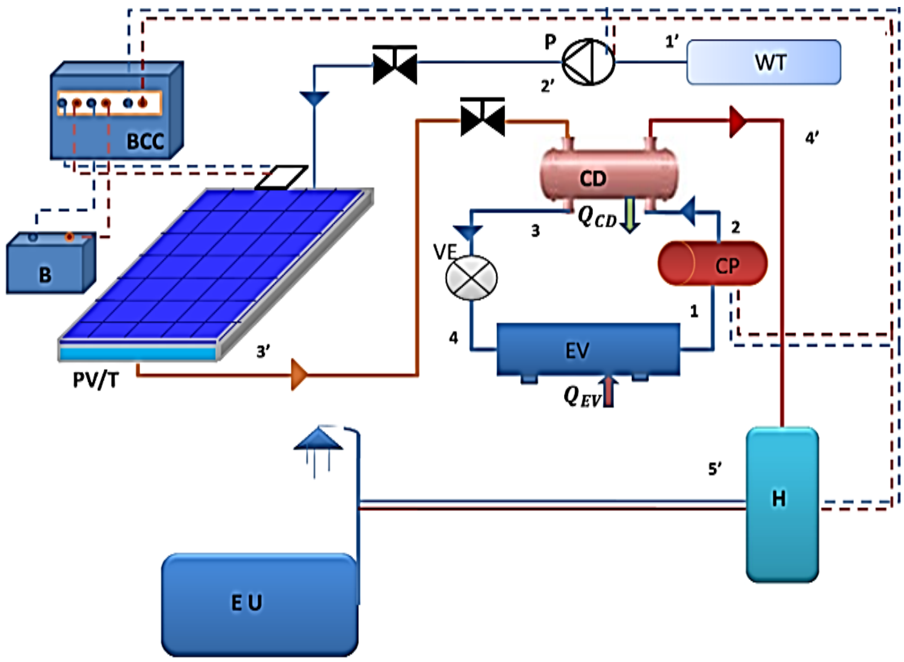

Fig. 1. Schematic diagram of the studied system; B: Battery, BCC: Battery Charge Controller, CD: Condenser, CP: Compressor, EU: End Use, EV: Evaporator, H: Heater (electrical resistance), P: Pump, PV/T: Hybrid Photovoltaic / Thermal system, VE: Expansion Valve, WT: Water Tank.

The PV/T solar field is using water as the working fluid, while the cooling part is based on a simple vapor compression cycle with R134a. Water primarily acts as a cooling agent for the panel in the PV/T system, increasing the electrical power production. In contrast, the water exiting the collector acts as a heat source for this system, allowing the condenser to be cooled by absorbing heat from the vapor that comes from the compressor and allowing it to be condensed.

In state 1, the refrigerant R134a is in a gaseous condition and at a low temperature and pressure, then the required power can be generated from PV module. In state 2, the R134a is at a higher pressure at the gaseous condition. The solar field increases the temperature of the water to (state 3') which will enter the condenser and acts as a heat exchanger in order to transfer the heat from the refrigerant to the water flow which exits at a higher temperature (state 4'). The heat is rejected from the condenser (Q_{CD}) to change from a gaseous state to a liquid one. When the refrigerant enters the expansion valve (state 3), it expands and the temperature begins to decrease at this point. In state 4 the refrigerant is a liquid vapor combination), hence, Q_{EV} represents the heat received to the evaporator.

2.2. Mathematical modeling

2.2.1. Modeling of the PV/T system

Fig. 2.a. shows a cross section of the proposed photovoltaic/thermal (PV/T) collector. The investigated system consists of a transparent glazing at the collector's, solar cell, the absorber and a rectangular duct formed by the top Tedlar and the insulation. The latitude of Jijel in North-East of Algeria (latitude 36°49′ N, longitude 5°46′ E, altitude 9 m) is used as the inclination angle of the simulated hybrid PV/T solar collector.

Fig.2.a demonstrates different heat transfer modes along various elements of the collector, and a permanent mathematical model under forced convection has been developed to analyze the PV/T performances, while Fig.2.b gives the equivalent electrical diagram of the PV/T system. It is necessary to make some assumptions and boundary conditions to model the considered system, these assumptions can be summarized as follows: the temperature gradient is negligible across thickness and width of components; the physical proprieties of materials are assumed to be constant. More details regarding the model are demonstrated in many papers [2, 19], so after some mathematical manipulation the following temperatures were calculated, as:

- **The cell temperature**

$$T_c = \frac{\tau_g[\alpha_c I(t)\beta_c + (1-\beta_c)\alpha_T I(t)] + U_t T_a + U_T T_t - \eta_c I(t)\beta_c}{U_t + U_T} \tag{1}$$

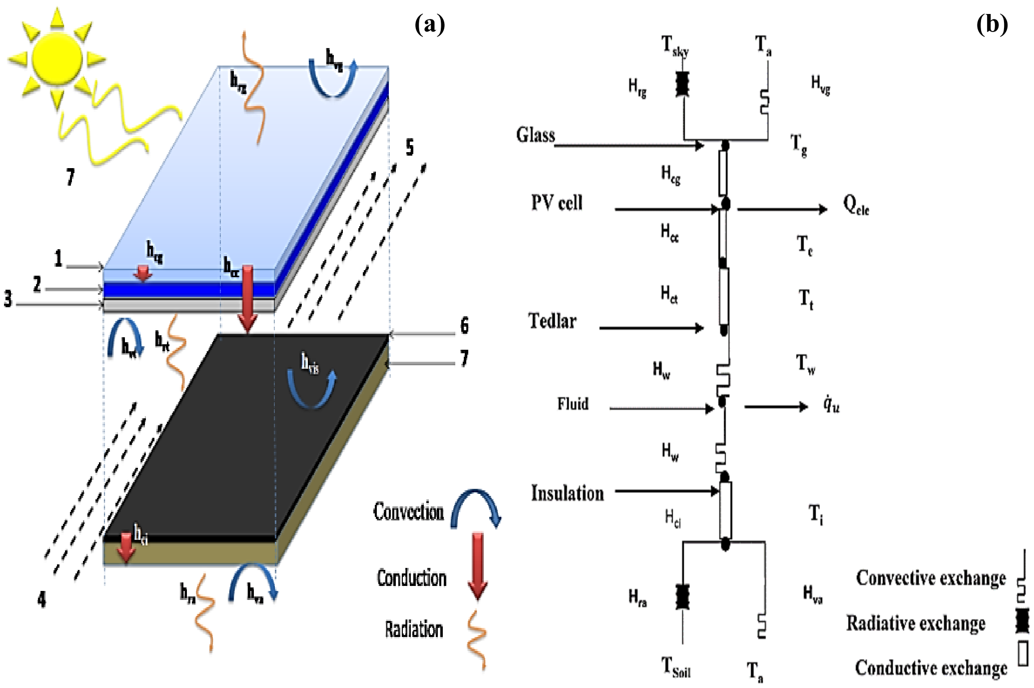

Fig. 2. a A cross sectional view of the hybrid PV/T solar collector; 1: Glass, 2: PV Cell, 3: Tedlar, 4: Fluid In, 5: Fluid Out, 6: Back plate, 7: insulating, 8: Solar Radiation. b. Equivalent electrical diagram of the PV/T system.

Table 1

The various coefficients and calculating equations

Coefficients	Equation	N°
The product of effective absorptivity and transmissivity	$(\alpha\tau)_{eff} = \tau_g\{\alpha_c\beta_c + \alpha_T(1-\beta_C) - \eta_c\beta_c\}$	(4)
The overall heat transfer coefficient from glass to tedlar	$U_{tT} = [\frac{1}{U_T} + \frac{1}{U_t}]^{-1} = \frac{U_T U_t}{U_t + U_T}$	(5)
The penalty factor due to tedlar through glass, solar cell and EVA (ethylene vinyl acetate which is encapsulation material for crystalline silicon solar cells)	$h_{p1} = \frac{U_T}{U_t + U_T}$	(6)
The penalty factor due to the presence of tedlar between glass cover and the working fluid	$h_{p2} = \frac{h_w}{U_{tT} + h_w}$	(7)
The overall heat transfer coefficient from the glass to the water through the solar cell and the tedlar	$U_t = [\frac{1}{U_{tT}} + \frac{1}{h_w}]^{-1} = \frac{h_w U_{tT}}{h_w + U_{tT}}$	(8)
The overall heat loss coefficient from the duct to the ambient	$U_L = U_{tw} + U_b$	(9)
The convective heat transfer coefficient between the back plate and the tedlar	$500\frac{W}{m^2.K}$, (referring to the study of Tiwari [2])	(10)

- **The tedlar temperature**

$$T_t = \frac{h_{p_1}(\alpha\tau)_{eff} I(t) + U_{tT} T_a + h_w T_w}{U_{tT} + h_w} \quad (2)$$

The average water temperature, can be determined by using the following initial condition: at $x = L, T_{wout} = T_w|_{x=L}$, as follows:

- **The average water temperature**

$$\bar{T}_w = \frac{1}{L}\int_0^L T_w dx = \left[\frac{h_{p1} h_{p2} (\alpha\tau)_{eff} I(t)}{U_L} + I(t)\right]\left(1 - \frac{1 - e^{-(bU_L/\dot{m}_w c_w)L}}{bU_L/\dot{m}_w c_w}\right) + T_{win}\frac{1 - e^{-(bU_L/\dot{m}_w c_w)L}}{bU_L/\dot{m}_w c_w} \quad (3)$$

.

Table 2

The inputs and dimensions of the PV/T collector [2, 14]

Parameter	Symbol	Value
Length of PV/T module	L	1.105 m
Width of PV/T module	B	0.467 m
Electrical parameters		
Solar cell type at Standard Test Conditions (STC); Irradiation of 1000 W/m^2 and temperature of 25°C		Silicon solar cell
Electrical efficiency of solar cell at reference conditions	β_{ref}	0.12
Temperature coefficient of the electrical power	β_p	0.0045 °C^{-1}
Reference cell temperature	$T_{c,ref}$	25 °C
Packing factor	β_c	0.90
Conversion factor of the thermal power plant	C_f	0.38
Thermal and design parameters		
Thickness of the glass cover	L_g	0.0030 m
Thickness of the solar cell	L_c	0.0003 m
Thickness of the tedlar	L_t	0.0005 m
Thickness of the back plate	L_{bp}	0.0030 m
Thickness of the insulation	L_i	0.0500 m
Conductivity of the glass cover	K_g	1 W/(m .°C)
Conductivity of the solar cell	K_c	0.039 W/(m .°C)
Conductivity of the tedlar	K_t	0.033 W/(m .°C)
Conductivity of the back plate	K_{bp}	386 W/(m .°C)
Conductivity of the insulation	K_i	0.035 W/(m .°C)
Transmissivity of the glass	τ_g	0.9
Absorptivity of the solar cell	α_c	0.85
Absorptivity of the tedlar	α_t	0.5
Emissivity of the glass	ε_g	0.88
Wind speed	V_{wind}	1 m/s
Specific heat capacity of water	c_w	4200 J/(kg. K)

The various coefficients presented in equations (1)-(3) are determined in Table 1 and more details are demonstrated in many papers [2, 14], while the Table 2 gives the inputs (at design point) and dimensions of the PV/T system with water as working fluid. Whereas, Table 3 illustrates the calculation of efficiencies.

Table 3

The calculation of efficiencies

Parameter	Equation	N°
The useful thermal energy	$\dot{q}_u = \frac{\dot{m}_w c_w}{U_L}\left[h_{p1}h_{p2}(\alpha\tau)_{eff}I(t) - U_L(T_{win} - T_a)\right]\left(1 - e^{-\frac{bU_L}{\dot{m}_w c_w}L}\right)$	(11)
The electrical efficiency	$\eta_{el} = \eta_{ref}\left[1 - \beta_p\left(T_c - T_{c,ref}\right)\right]$	(12)
The daily thermal efficiency of the PV/T collector	$\eta_{th} = \frac{\sum_{i=t1}^{t2} \dot{q}_u}{\sum_{i=t1}^{t2} I(t)bL}$	(13)
The overall efficiency	$\eta_{PVT} = \frac{\eta_{el}}{C_f} + \eta_{th}$	(14)

2.2.2. Thermodynamic model

The following assumptions are considered for this evaluation [11]: the pressure drops in all elements of the system has been neglected. The potential and kinetic energies are ignored. The condenser's outlet fluid is saturated, whereas the evaporator's outlet fluid is at gaseous state. Table 4 summarizes the equations used for mathematical modelling of the heating/cooling system, where h represents the specific enthalpy of working fluid at the corresponding state point (kJ/kg). Then, table 5 gives the efficiencies formula and the inputs and data to design and simulate the proposed system are shown in Table 6.

Table 4

Energy and mass balance equations of the proposed system components

Elements	Energy balance equation	Mass balance equation
Compressor	$\dot{W}_{CP,s} = \dot{m}_2 h_{2,s} - \dot{m}_1 h_1$ $\dot{W}_{CP} = \frac{\dot{W}_{CP,s}}{\eta_{el}}$	$\dot{m}_1 = \dot{m}_2$
Condenser	$\dot{Q}_{CD} = \dot{m}_2 h_2 - \dot{m}_3 h_3$	$\dot{m}_2 = \dot{m}_3$
Expansion valve	$h_4 = h_3$	$\dot{m}_4 = \dot{m}_3$
Evaporator	$\dot{Q}_{EV} = \dot{m}_1 h_1 - \dot{m}_4 h_4$	$\dot{m}_4 = \dot{m}_1$
Pump	$\dot{W}_{pump} = (\dot{m}_{2'} h_{2'} - \dot{m}_{1'} h_{1'})/\eta_{pump}$	$\dot{m}_{2'} = \dot{m}_{1'}$
Electrical resistance	$\dot{W}_{R,ele} = \dot{m}_{5'} h_{5'} - \dot{m}_{4'} h_{4'}$	$\dot{m}_{5'} = \dot{m}_{4'}$

Table 5

The efficiencies formula

Parameter	Equation	N°
Cooling coefficient of performance [11, 15]	$\mathrm{COP} = \frac{\dot{Q}_{EV}}{\dot{W}_{CP}} = \frac{\dot{m}_1 h_1 - \dot{m}_4 h_4}{\dot{m}_2 h_2 - \dot{m}_1 h_1}$	(15)
Solar system's cooling efficiency [11]	$\eta_{sol-cool} = \frac{\dot{Q}_{EV}}{b\, L\, I(t)}$	(16)
Solar system's heating efficiency [11]	$\eta_{sol-heat} = \frac{\dot{Q}_{heat}}{b\, L\, I(t)}$	(17)
The total heat absorbed by water	$\dot{Q}_{heat} = \dot{m}_w c_w (T_{4'} - T_{2'})$	(18)

Table 6

Design Parameters for the vapor compression system [11]

Parameter	Value
Compressor isentropic efficiency	0,9343 (at p_2=1000 kPa)
Pump isentropic efficiency	0,9
Condenser temperature	34 °C
Evaporator temperature	−20 °C
PV/T's inlet water temperature	27 C

3. Results and discussion

3.1. Validation of the model

In this study, the numerical modelling and simulations have been performed using Matlab R2014a software [16].

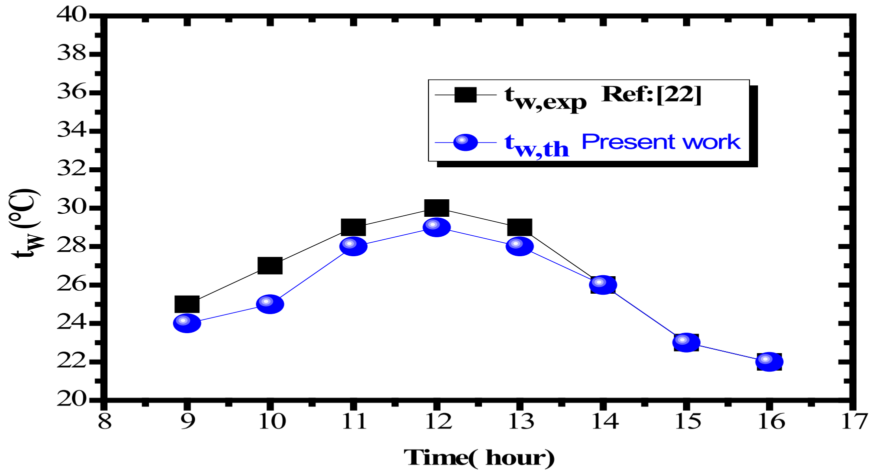

Fig. 3. Comparison between present work and Bahaidarah et al [17] data points for the variation of the outlet temperature of water.

Fig. 3 shows the comparison study of the current analytical outlet temperature of water from PV/T system (present simulation work) with the outlet temperature found in Bahaidarah et all's experimental study during a typical day [17]. The figure depicts the variation of the outlet temperature of water as a function of the time and the results obtained are very similar to those published by Bahaidarah et al [17]. The current study's findings forecast water outlet temperature to within a relative error of 2.84%, which could be due to the application of hypotheses and uncertainties in the correlations employed in the mathematical analysis.

3.2. Performances of the system at the design point

The cycle's system energy analysis was carried out for the R134a fluid and the water as secondary working fluid, under the following operating conditions: the desired cooling capacity to the domestic application. (P_{cool}) is 90 kW, t_{hw}=40°C, $\dot{m}$=5 kg/s, I(t)=945 W/m^2.

Table 7

Thermodynamic properties of the system at the nominal conditions

Point	t [C°]	p [kPa]	h [kJ/kg]	$\dot{m}$ [kg/s]
1	-20.0	131.88	386.46	0.687
2	50.9	1000.00	431.70	0.687
3	39.5	1000.00	255.50	0.687
4	-20.0	131.88	255.50	0.687
1'	27.0	100.00	112.65	5.000
2'	26.8	220.00	112.65	5.000
3'	35.2	220.00	147.17	5.000
4'	66.9	220.00	279.71	5.000
5'	40.0	220.00	167.09	5.000

Table 8

Thermodynamic performances of the system at the nominal conditions

Parameter	Value
P_{elec} [kW]	31.75
N_{panels} [-]	377
$\eta_{PV/T,elec}$ [%]	11.01
$\eta_{PV/T,therm}$ [%]	49.44
$\eta_{PV/T,glob}$ [%]	78.43
COP [-]	2.89
$\eta_{solar\text{-}cool}$ [%]	45.16
$\eta_{solar\text{-}heat}$ [%]	41.92

The thermodynamic characteristics of each state in the coupled solar-cooling system are reported in Table 7 as well as, the PV/T system, solar cooling and solar heating thermodynamic efficiencies are listed in Table 8. As results, this table shows that the system requires 377 PV/T panels to be connected, and the overall efficiency of the PV/T system is significant under the operating parameters chosen and takes a value of 78.43%. The solar-cooling and solar - heating performances of the coupled solar-cooling system are also significant: 45.16%and 41.92 % respectively.

3.3. Effect of the different parameters on the performances of the system

3.3.1. Effect of required power for cooling $\dot{Q}_{EV}$

It can be observed in Fig.4, the influence of the required power for cooling $\dot{Q}_{EV}$ on the performance of the system. As the cooling power increases, the number of the panels required for the system increases which also requires an increase in the demand. In parallel, the raising in the cooling power also leads to an increase in the requested flow rate of the refrigerant $\dot{m}$ from 0 to 1.5271kg/s.

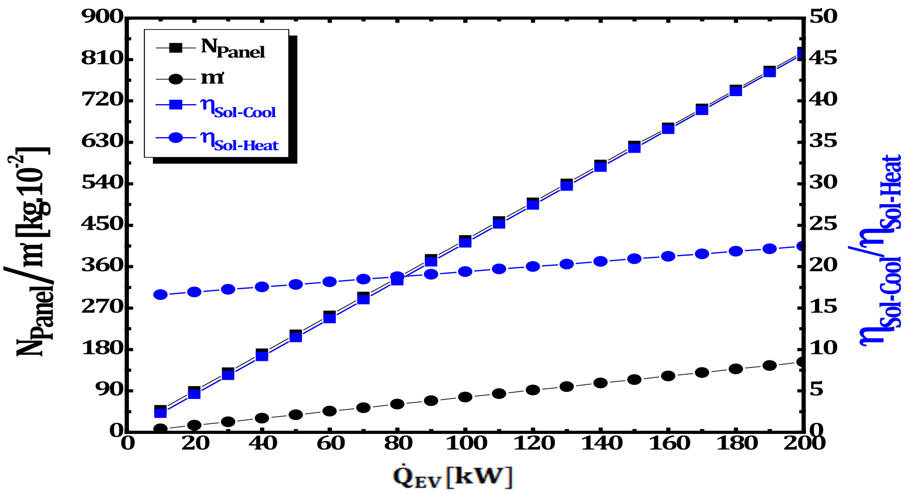

Fig. 4. Influence of required performances for cooling $\dot{Q}_{EV}$ at I (t) =945W/m^2

From Fig. 4, it can be found that when cooling power increases from 0 kW to 200kW, both solar-cooling and solar-heating efficiencies values increase from 0 to 45.69% and from 0 to 22.46%, respectively. This is explained by the fact that the cooling power of the cycle increases as the temperature of the refrigerant at the condenser outlet decreases, and as this temperature decreases, the discharge pressure of the compressor decreases, lowering the compression ratio and compressor input power. It should be noted that raising the compressor's inlet power during the daytime results in an increase in refrigeration capacity. The capacity of the evaporator is significantly impacted by the usage of water for panel cooling, as is evident [20]. These results are consistent with those reported in Chen et al [18], who found that lower condensing temperatures can result in improved cooling system performance.

3.3.2. Effect of required mass flow rate of the heating water

Fig. 5 illustrates how the number of panels, heating power, and solar heating efficiency change when the water flow changes. When the flow of water is increased from 0 to 10 kg/s, the heating power and solar heating efficiency rise considerably from 4285.27 kW to 12855.8 kW and from 21.78% to 53.18% respectively. The heat transfer coefficient improves as the area of captation rises, resulting in increased solar system performance as the number of panels increases. Due to the larger temperature difference that will be formed in the solar collector, more heat flux will be absorbed by water. As a result, the heating power rises because the temperature difference between the condenser's inlet and outlet causes overheating of the water at the outlet, while the refrigerant is subcooled. As a result, the solar heating's effectiveness improves.

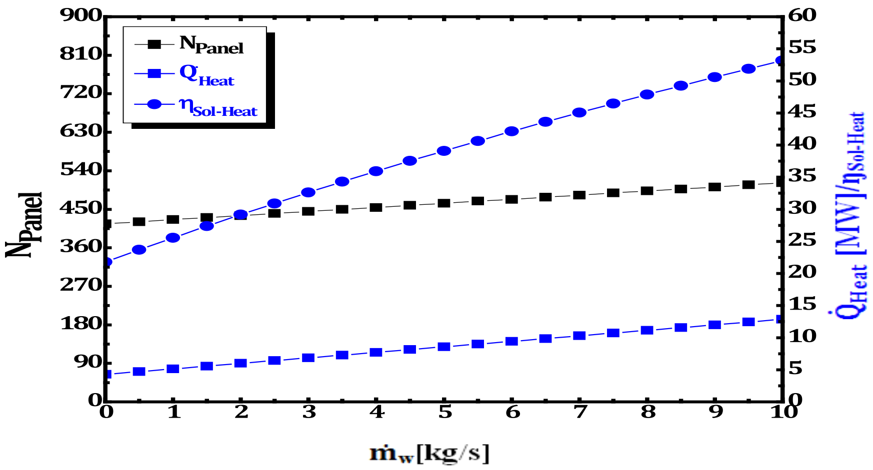

Fig. 5. Effect of the mass flow rate of heating water at I(t) = 945 W/m^2

As a result, altering the water flow rate will have an impact on the refrigeration cycle. These effects include: Increasing the water flow rate increases the PVT production capacity, decreasing the PVT output temperature, decreasing the input to the condenser, and increasing cycle efficiency. Increasing the flow rate has several advantages. However, increasing the water flow results in higher pumping power and energy waste [20].

3.3.3. Effect of solar radiation

Fig. 6 depicts the changes in the number of panels and solar heating and cooling efficiency of the combined PV/T-cooling system. With an increase in solar radiation intensity, solar heating and cooling efficiency improve, while the number of panels required decreases. Because the specific heat of the water is high, increasing solar irradiation raises the temperature of the water exiting the collector, eliminating the need for a large exchange surface. More specifically, the thermal energy that the water obtains during the day increases as the sun irradiation and ambient temperature rise. As a result, this temperature becomes warmer. Solar heating and cooling efficiencies, on the other hand, improve as solar radiations rise. When this parameter rises from 200 W/m^2 to 1200 W/m^2, the solar heating efficiency rises from 2.00% to 66.11% while the solar cooling efficiency rises from 2.15 % to 71.24%. Because the heat transported to the condenser in a refrigeration cycle is equal to the total of the compressor's effort and the evaporator's capacity, this is the case. As the water temperature difference rises, more heat is delivered to the water via the condenser, increasing both solar heating and cooling efficiency.

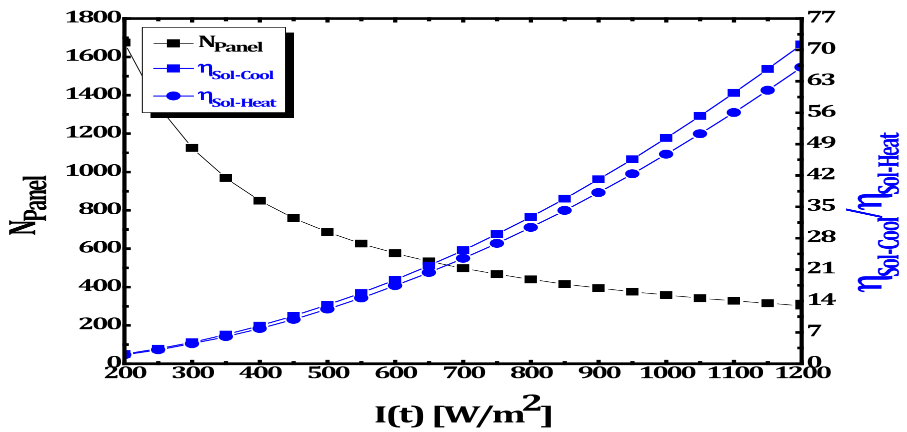

Fig. 6. Effect of solar radiation on the number of panels in the solar field and efficiencies of the system.

As results this enhances the sub-cooling of the refrigerant leaving the condenser, the evaporator's capacity improves as well. The findings are in good agreement with the results reported by Zarei et al [11].

3.4. Simulation the performances of the system under Jijel climatic conditions

For 17 May 2017, the solar hybrid photovoltaic /thermal system were explored under Jijel's (Lat: 36.81°N , Lon: 5.74°E) prevalent weather conditions. The hourly changes of the measured solar radiation are shown in Fig. 7, as well as the different efficiencies which are: the overall PV/T efficiency η_{PVT}, the solar heating efficiency $\eta_{sol-heat}$ and the solar cooling efficiency $\eta_{sol-cool}$. The maximum value of solar radiation I(t) is 910 W/m^2 and can be found in Fig. 8's data at 1:00 pm, while the minimum values are 270 W/m^2 at 8:00 am and 5:00 pm.

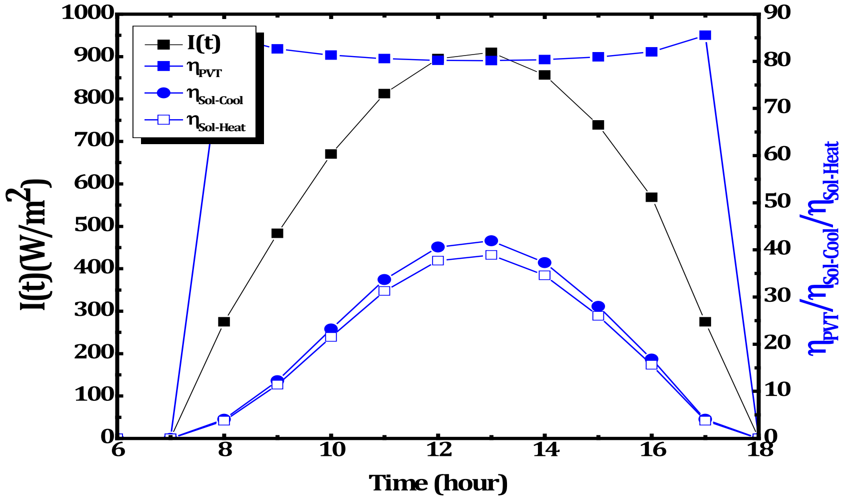

Fig. 7. Variation of solar radiation and different efficiencies of the combined PV/T- cooling system vs. time on a typical day of May 2017 for $\dot{m}_W = 0.013kg/s$

In term of efficiencies, Fig. 8 depicts that the evolution of the solar heating and cooling efficiencies corresponds to the evolution of solar radiation (see Eqs. (16), (17)) and the maximum values of the solar heating efficiency and the solar cooling efficiency are obtained as 38.93% and 41.94%, respectively; whereas, at 1:00 pm a minimum value is found to be 80.2% for the overall PV/T efficiency η_{PVT}, since it is generally known that when the temperature of the solar cells rises, the electrical efficiency falls, the value of the overall efficiency falls as well when calculated by adding thermal efficiency to the electrical efficiency which must be converted into equivalent thermal efficiency. These results are in good agreement with that reported by Joshi et al [14]. In parallel, for the hourly variation of the solar cooling and heating performance coefficients of the refrigerant used R134a with a mass flow rate of the water fluid equal to 0.013kg/s if the solar irradiance increases, the water temperature of the collector output increases, resulting in increased cooling of the refrigerant leaving the condenser and the capacity of the evaporator as mentioned above.

4. Conclusion

In the present study, a hybrid solar PV/T-cooling system based on vapor compression refrigeration cycle with R134a has been designed, and its performances were simulated for household applications. In order to investigate thermal and electrical performances of the water-cooled PV/T system, as well as thermodynamic efficiencies of the cooling and heating cycles, a detailed numerical model was developed under Matlab environment. The simulations carried out on the effects of different operating parameters on the performances of the system lead to the following conclusions:

- The model was validated, and the results of this model are in good agreement with Bahaidarah's [22] experimental findings for PV/T water outlet temperature.
- The increase in cooling power in the evaporator corresponds to an increase in the needed flow rate of the refrigerant up to 1.5271 kg/s. Moreover, the efficiencies of solar cooling and heating have increased up to 45.69% and 22.46 % respectively.
- The effects of water mass flow rate on solar heating efficiency and generated heat are also investigated. They both increased significantly when the water flow rate is increased from 0 to 10 kg/s; which they vary from low values of 4285.27 kW and 21.78 %, to high ones (12855.8 kW and 53.18 %) respectively.
- With the increasing in solar radiation, the system's heating and cooling efficiencies are improved.
- Under Jijel's typical weather conditions at a high irradiation value that can reach 910 W/m^2, the hybrid system can reach maximum values of heating and cooling efficiencies of 38.93 %t and 41.94 % respectively, although the overall PV/T efficiency, gives a minimum value of 80.2 %.

The presented model in this work needs to be updated and enhanced to take into account different dimensions such as exergetic, economic, environmental parameters. Furthermore, different working fluids in both heating and cooling cycles should be investigated in future works in order to choose the best layout to be adopted in this combined system.

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