WATER COOLING OF PHOTOVOLTAIC PANELS FROM PASSIVE HOUSE LOCATED INSIDE THE UNIVERSITY POLITEHNICA OF BUCHAREST

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Inside the Polytechnic University of Bucharest are located two passive houses one in front of the other. On the south side of each house are located 13 photovoltaic panels with a nominal power of 3kW. The purpose of this article is to maximize the efficiency of the solar cells. Temperatures in excess may cause degradation of photovoltaic panels. By altering various physical parameters of the heat exchanger in the PV water system, the maximum efficiency is aimed. This information can be used in maximizing the efficiency of any collector design.

Fig. 1. The passive house

Keywords: water cooling; photovoltaic panel; passive house; thermal efficiency

1. Introduction

A major problem we encounter in designing photovoltaic panels is increasing their efficiency. An efficiency increase also means an increase of electricity production. Therefore this article has attempted to present a way to increase the efficiency of photovoltaic panels by cooling them with water. It is a water cooling system, which functions as a heat exchanger. With this system the panels temperature decreases, so the electricity production is increased. It is a

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theoretical research that can be implemented in the passive house inside the Polytechnic University of Bucharest.

2. Research

2.1. PV/W system

In order to investigate how various parameters affect the overall efficiency of the system a spreadsheet was developed. The spreadsheet was based on the water-cooled PV panel. Some graphs of the spreadsheet will be presented and discussed in this part of the article. Nevertheless, the whole theory behind the calculations should first be presented.
The general configuration of the water-cooled system is presented in Fig. 2.

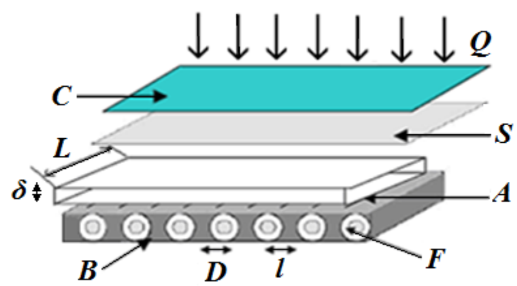

Fig. 2. The PV/W model

Q - the heat transfer
C - the cover of the system
S - the solar panel
L - tube length
δ - the thickness of the absorber
A - the absorber
B - the heat exchanger
D - diameter of the tube
l - distance between two tubes
F - fluid passing through the tubes

A series of tubes, trough which cold water passes, were mounted below the solar panel. The tubes works as a heat exchanger, cooling the solar panel.
Between the heat exchanger's tubes is the absorber with thickness δ. Each of the above components is characterized by various important parameters. These are the absorbance $\alpha(\lambda)$, emissivity $\varepsilon(\lambda)$, reflectivity $\rho(\lambda)$ and transmittance $\tau(\lambda)$. These

generally obey $\rho(\lambda)+\alpha(\lambda)+\tau(\lambda)=1$ and $\alpha(\lambda)=\varepsilon(\lambda)$. Energy can be exchanged by conduction, convection and radiation [1,2,3]. The conductive and convective terms are linear in the temperature difference. They are characterized by the generalized conductance U_{xy} between the components x and y. For example, U_{SA} is the conductance between the solar cell and the absorber while U_{Aa} is the sum of edge and bottom losses due to conductance and convection.

2.2. The theoretical research

Energy conservation in steady state for the area above the tubes gives [4]:
For the fluid:

$$q \cdot D^{-1} + U_{Fa} \cdot (T - T_a) = U_{AF} \cdot (T_A - T) \quad (1)$$

For the absorber:

$$U_{AF} \cdot (T_A - T) + U_{Aa} \cdot (T_A - T_a) + \{\varepsilon_A \cdot \alpha_A\} \cdot \sigma \cdot T_A^4 = \\ = U_{SA} \cdot (T_S - T_A) + \{\varepsilon_S \cdot \alpha_A\} \cdot R_S + \{\varepsilon_C \cdot \tau_S \cdot \alpha_A\} \cdot \sigma \cdot T_C^4 + \{\tau_C \cdot \tau_S \cdot \alpha_A\} \cdot G + \\ q_f \cdot D^{-1} \quad (2)$$

For the solar cell:

$$P(T_S) + U_{SA} \cdot (T_S - T_A) + U_{SC} \cdot (T_S - T_C) + \{\varepsilon_S \cdot \alpha_S\} \cdot R_S = \\ = \{\tau_C \cdot \alpha_S\} \cdot G + \{\varepsilon_C \cdot \alpha_S\} \cdot \sigma \cdot T_C^4 + \{\varepsilon_A \cdot \alpha_S\} \cdot \sigma \cdot T_A^4 \quad (3)$$

The above formulae contain terms in curly braces. These terms represent geometric series due to multiple reflections and transmissions The table below lists the most important ones [5].

$$\{\varepsilon_A \alpha_A\} = \varepsilon_A \cdot \left(1 - \frac{\alpha_A \cdot \rho_S \cdot (1-\rho_S \cdot \rho_C) + \tau_S^2 \cdot \rho_C}{(1-\rho_S \cdot \rho_C) \cdot (1-\rho_S \cdot \rho_A) - \tau_S^2 \cdot \rho_A \cdot \rho_C}\right) \quad (4)$$

$$\{\varepsilon_A \cdot \alpha_S\} = \varepsilon_A \cdot \alpha_S \cdot \left(\frac{1-\rho_S \cdot \rho_C + \tau_S \cdot \rho_C}{(1-\rho_S \cdot \rho_C) \cdot (1-\rho_S \cdot \rho_A) - \tau_S^2 \cdot \rho_A \cdot \rho_C}\right) \quad (5)$$

$$\{\tau_C \cdot \tau_S \cdot \alpha_A\} = \tau_C \cdot \tau_S \cdot \alpha_A \cdot \left(\frac{1}{(1-\rho_S \cdot \rho_C) \cdot (1-\rho_S \cdot \rho_A) - \tau_S^2 \cdot \rho_A \cdot \rho_C}\right) \quad 6)$$

$$\{\tau_C \cdot \alpha_S\} = \tau_C \cdot \alpha_S \cdot \left(\frac{1-\rho_S \cdot \rho_A + \tau_S \cdot \rho_A}{(1-\rho_S \cdot \rho_C) \cdot (1-\rho_S \cdot \rho_A) - \tau_S^2 \cdot \rho_A \cdot \rho_C}\right) \quad (7)$$

Some approximations have been made in order to simplify calculations [6]:

- ➔ all material properties are presumed to be independent of temperature and equal on both sides;
- ➔ the components are presumed to be thin enough to allow for neglecting temperature gradients through them;

- the heat transport to the collector plane is independent of the heat transport in the plane;
- the ambient temperature is considered to be equal on all sides of the collector;
- all in and out of the fluid radiation are neglected;
- the fluid is properly isolated from the environment, mean that the term $U_{Fa}(T\text{-}T_a)$ is neglected;
- the R_s terms can also be neglected because the solar cell radiation is small.

An infinitesimal segment with Δx width is considered in order to find the heat transport q_f from the fin to the tube. The energy balance equation for this segment is:

$$U_{Aa} \cdot (T_{Af} - T_A) \cdot \Delta_x + \{\varepsilon_A \cdot \alpha_A\} \cdot \sigma \cdot T_{Af}^4 \cdot \Delta_x = U_{SA} \cdot (T_S - T_{Af}) \cdot \Delta_x + \{\tau_c \cdot \tau_s \cdot \alpha_A\} \cdot G \cdot \Delta_x - \lambda \cdot \delta \cdot \frac{\mathrm{dT_{Af}}}{\mathrm{dx}}\bigg|\, x + \lambda \cdot \delta \cdot \frac{\mathrm{dT_{Af}}}{\mathrm{dx}}\bigg|\, x + dx \quad (8)$$

The solar cell temperature may be found calculated using the balance equation (3):

$$\lambda \cdot \delta \cdot d^2 T_{Af}/dx^2 = U'_{Aa} \cdot (T_{Af} - T_a) + F_R \cdot \sigma \cdot T_{Af}^4 - S \quad (9)$$

The following notation has been used:

$$U'_{Aa} = U_{Aa} + U_{SA} \cdot (U_{Sa} - c \cdot G)/U_{SA} + U_{Sa} - c \cdot G \quad (10)$$

$$F_R = \{\varepsilon_A \cdot \alpha_A\} - U_{SA} \cdot \{\varepsilon_A \cdot \alpha_S\}/U_{SA} + U_{Sa} - c \cdot G \quad (11)$$

$$S = (\{\varepsilon_A \cdot \alpha_A\} - U_{SA} \cdot (\{\tau_c \cdot \alpha_S - \eta_0\})/U_{SA} + U_{Sa} - c \cdot G) \cdot G \quad (12)$$

Due to the radiation term the differential equation has no analytical solution and an approximation should be done. Around $T_{Af}=T_a$ the right hand side is almost linear in $(T_{Af}\text{-}T_a)$,
and a Taylor expansion is quite accurate:

$$\lambda \cdot \delta \cdot d^2 T_{Af}/dx^2 \approx F_R \cdot \sigma \cdot T_a^2 - S + U''_{Aa}(T_a) \cdot (T_{Af} - T_a) \quad (13)$$

The modified loss factor is :

$$U''_{Aa}(T_a) = U'_{Aa} + 4 \cdot F_R \cdot \sigma \cdot T_a^3 \quad (14)$$

Which also accounts for radiation losses. In combination with the boundary conditions [7]:

$$\left.\frac{dT_{Af}}{dx}\right|_{x=0} = 0 \quad (15)$$

$$T_{Af} \cdot (l - D)/2 = T_A \quad (16)$$

Where l is the width of one unit ,this gives:

$$T_{Af}(x) = T_a + \frac{S - F_R \cdot \sigma \cdot T_a^4}{U''_{Aa}(T_a)} - \left(T_a + \frac{S - F_R \cdot \sigma \cdot T_a^4}{U''_{Aa}(T_a)} - T_A\right) \cdot \frac{\cosh(\omega x)}{\cosh\left(\omega \cdot \frac{(l-D)}{2}\right)} \quad (17)$$

Where :

$$\omega^2 = U''_{Aa}(T_a) \cdot (\lambda \cdot \delta) - 1 \quad (18)$$

The heat brought to the tube from the two half fins is thus:

$$q_F = -2 \cdot \lambda \cdot \delta \cdot \left.\frac{dT_{Af}}{dx}\right|_{x=\frac{(l-D)}{2}} = (l - D) \cdot F_f \cdot \left(S - F_R \cdot \sigma \cdot T_a^4 - U''_{Aa}(T_a) \cdot (T_A - T_a)\right) \quad (19)$$

The fin factor F_f is defined as:

$$F_f = \frac{\tanh\left(\omega \cdot \frac{(l-D)}{2}\right)}{\omega \cdot \frac{(l-D)}{2}} \quad (20)$$

The fin factor is a measure on how effectively the heat is transported from the fin to the tube via the absorber [8]. Having found the heat from the two half fins, it is straightforward to solve the balance equations (1)-(3) to find the following expression for the generalized heat:

$$q(T) = l \cdot F(T) \cdot [s - F_R(T) \cdot \sigma \cdot T^4 - U_L \cdot (T - T_a)] \quad (21)$$

The collector efficiency factor $F(T)$ is given by:

$$F(T) = \frac{\frac{D}{l} \cdot \left(1 + \frac{l-D}{D} \cdot F_f\right)}{1 + \frac{\left(U_L \cdot \left(1 + \frac{l-D}{D} \cdot F_f\right) + 4 \cdot F_R \cdot \sigma \cdot T^3\right)}{U_{AF}}} \quad (22)$$

The effective radiation loss factor as:

$$F_R(T) = \frac{1 + \frac{l-D}{D} \cdot F_f \cdot \frac{T_a^4}{T^4}}{1 + \frac{l-D}{D} \cdot F_f} \cdot F_R \quad (23)$$

And the total conductive loss factor as :

$$U_L = \frac{U'_{Aa} + \frac{l-D}{D} \cdot F_f \cdot U''_{Aa}(T_a)}{1 + \frac{l-D}{D} \cdot F_f} \tag{24}$$

The rate of heat that it is drawn from the system is:

$$Q_T = \dot{m} \cdot c_p \cdot (T_L - T_i) \tag{25}$$

Where the outlet temperature T_L is the fluid temperature at $y=L$. The thermal efficiency, most conveniently defined as the ratio of the generated heat to the incoming insolation, is given by:

$$\eta_A = \frac{Q_T}{G \cdot L \cdot l} = \frac{\dot{m} \cdot c_p}{G \cdot L \cdot l} \cdot \left(T_a - T_i - \frac{q(T_a)}{q'(T_a)} \cdot \left(1 - \exp\left(\frac{q'(T_a) \cdot L}{\dot{m} \cdot c_p}\right)\right)\right) \tag{26}$$

Where:

$$q'(T_a) = \left.\frac{dq}{dT}\right|_{T=T_a} \tag{27}$$

Which is the differentiated heat. After calculations the differentiated heat was found to be [9]:

$$q'(T_a) = l \cdot F'(T_a) \cdot S - l \cdot \sigma \cdot [\, F'(T_a) \cdot F_R(T_a) \cdot T_a^4 + F(T_a) \cdot F'_R(T_a) \cdot T_a^4 + \\ +4 \cdot F(T_a) \cdot F_R(T_a) \cdot T_a^3 \,] - l \cdot U_L \cdot (T_a - T_a) \cdot F'(T_a) \tag{28}$$

In order to find the above, the differentiated collector efficiency factor $F'(T_a)$ must be found as well as the differentiated effective radiation loss factor. After some relatively complex calculations:

$$F'(T_a) = -\frac{\frac{D}{l} \cdot \left(1 + \frac{l-D}{D} \cdot F_f\right) \cdot \left(\frac{12 \cdot F_R \cdot \sigma \cdot T_a^2}{U_{AF}}\right)}{1 + \left[\frac{U_L \cdot \left(l + \frac{l-D}{D}\right) \cdot F_f + 4 \cdot F_R \cdot \sigma \cdot T_a^3}{U_{Af}}\right]^2} \tag{29}$$

$$F'_R(T_a) = \frac{-4 F_R \cdot \frac{l-D}{D} \cdot F_f \cdot T_a^{-1}}{\left(1 + \frac{l-D}{D}\right) \cdot F_f} \tag{30}$$

2.3. Parametric analysis of the Water Cooled Panel

The parametric analysis of the water cooled photovoltaic is performed in order to establish the most important parameters which affect the operation of the

PV panel. These parameters can either be the physical properties of the heat exchanger connected to the panel as well as the flow of water inside the tubes.

Table 1

Table of initial data

l/D	-	1.25	0.833	0.625	0.5	0.417	0.357	0.313
$(l-D)/D$	-	0.25	-0.167	-0.375	-0.5	-0.583	-0.643	-0.688
l	m	0.025	0.025	0.025	0.025	0.025	0.025	0.025
D	m	0.02	0.03	0.04	0.05	0.06	0.07	0.08
T_i	K	280	280	280	280	280	280	280
m	kg/s	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
$\{\tau_c \alpha_s\}$	-	0.7	0.7	0.7	0.7	0.7	0.7	0.7
$\{\varepsilon_A \alpha_A\}$	-	0.1	0.1	0.1	0.1	0.1	0.1	0.1
$\{\tau_c \tau_s \alpha_A\}$	-	0.15	0.15	0.15	0.15	0.15	0.15	0.15
$\{\varepsilon_A \alpha_s\}$	-	0.05	0.05	0.05	0.05	0.05	0.05	0.05
G	W/m^2	800	800	800	800	800	800	800
η_0	-	0.138	0.138	0.138	0.138	0.138	0.138	0.138
c	-	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
T_a	K	310	310	310	310	310	310	310
U_{Aa}	W/m^{2}K	1	1	1	1	1	1	1
U_{AF}	W/m^{2}K	200	200	200	200	200	200	200
U_{SA}	W/m^{2}K	100	100	100	100	100	100	100
U_{Sa}	W/m^{2}K	6	6	6	6	6	6	6
k	W/mK	399	399	399	399	399	399	399
c_p	J/kgK	4200	4200	4200	4200	4200	4200	4200
δ	m	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
L	m	1.5	1.5	1.5	1.5	1.5	1.5	1.5
T	K	280	280	280	280	280	280	280
T_a	K	310	310	310	310	310	310	310
ω	-	5.86	5.86	5.86	5.86	5.86	5.86	5.86

After determining these factors and their importance the system efficiency can be maximized. In table 1 is presented the initial data and the variation of the diameter, and in table 2 is presented the calculated data and the variation of the thermal efficiency.

Table 2

Table of calculated data

$F(T)$	0.961	0.974	0.980	0.986	0.992	0.999	1.009
F_R	0.0527	0.0527	0.0527	0.0527	0.0527	0.0527	0.0527
S	540.25	540.25	540.25	540.25	540.25	540.25	540.25
$q(T)$	17.08	17.3	17.41	17.49	17.58	17.7	17.8564
F_f	0.9999	0.9999	0.9994	0.9982	0.9965	0.9942	0.9914
$F(T_a)$	0.9601	0.9730	0.9800	0.9854	0.9911	0.9984	1.0082
$F_R(T)$	0.0579	0.0474	0.0368	0.0263	0.0159	0.0058	-0.0040
U_L	6.3733	6.2328	6.0924	5.9529	5.8152	5.6807	5.5509
σ	5.6E-08	5.6E-08	5.6E-08	5.6E-08	5.6E-08	5.6E-08	5.6E-08

U'_{Aa}	6.303	6.303	6.303	6.303	6.303	6.303	6.303
$U''_{Aa}(T_a)$	6.6544	6.6544	6.6544	6.6544	6.6544	6.6544	6.6544
ω	5.86	5.86	5.86	5.86	5.86	5.86	5.86
$q(T_a)$	12.313	12.479	12.569	12.638	12.711	12.805	12.93
$F'(T)$	$-1.38*10^{-5}$	$-1.38*10^{-5}$	$-1.38*10^{-5}$	$-1.38*10^{-5}$	$-1.393*10^{-5}$	$-1.401*10^{-5}$	$-1.41*10^{-5}$
$F_R'(T)$	-0.00015	0.00015	0.00045	0.00075	0.00105	0.00134	0.00163
$F'(T_a)$	$-1.69*10^{-5}$	$-1.698*10^{-5}$	$-1.701*10^{-5}$	$-1.70*10^{-5}$	$-1.708*10^{-5}$	$-1.717*10^{-5}$	$-1.73*10^{-5}$
$F_R'(T_a)$	-0.00014	0.00014	0.00041	0.00068	0.00094	0.00121	0.00147
$F_R(T_a)$	0.05265	0.05265	0.05265	0.05265	0.05265	0.05265	0.05265
$q'(T_a)$	-0.00696	-0.01047	-0.01398	-0.01750	-0.02103	-0.02459	-0.02823
η_A	0.62360	0.63581	0.64414	0.65141	0.65890	0.66739	0.67750
η_A	62.36%	63.58%	64.41%	65.14%	65.89%	66.74%	67.75%

In order to observe how the thermal efficiency varies, the water mass flow is increased 10 times and the results shows that the thermal efficiency of the cooling system has almost the same values. That can be seen in Fig. 3 where the thermal efficiency depending on the ratio of the distance between two pipes and pipe diameter for the both values of mass flow of water was represented.

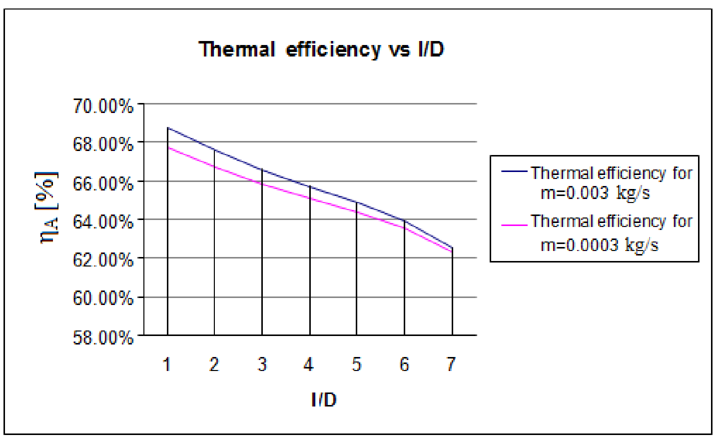

Fig.3. Thermal efficiency depending on the ratio of the distance between two pipes and pipe diameter for the both values of mass flow of water

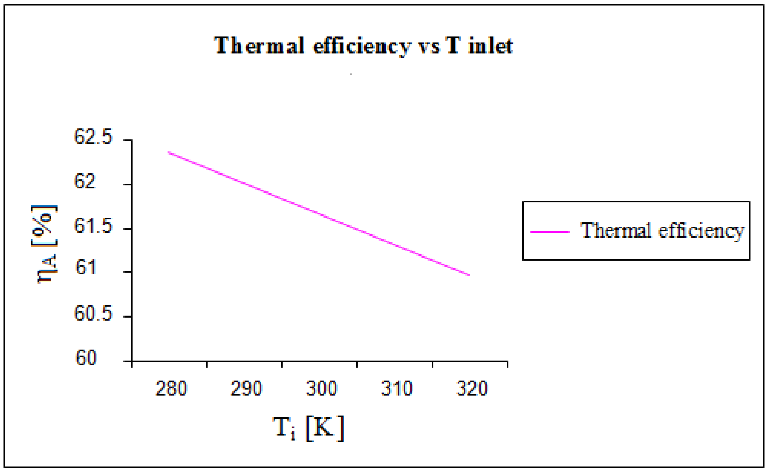

Fig.4. Thermal efficiency depending the inlet temperature of water

The inlet temperature of the water into the heat exchanger varied from 280 K to 320 K in order to see how the thermal efficiency is altered. As it was expected the efficiency dropped with increasing temperature and that can be observed in Fig. 4. The interesting point is that the variations of the temperature change were high, nevertheless the efficiency decreased slightly.

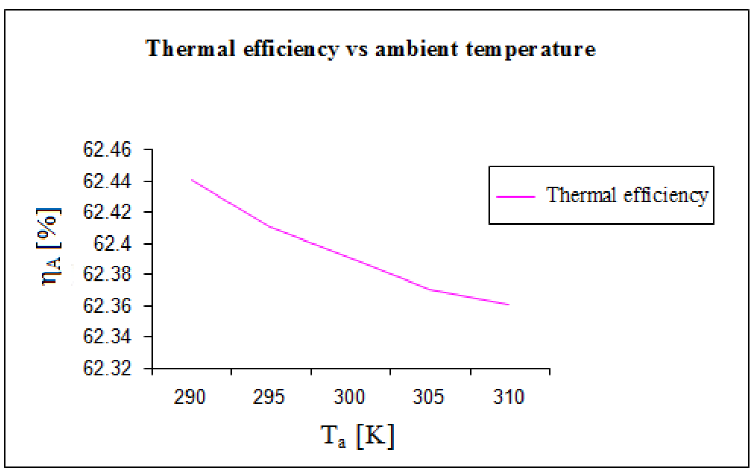

Fig.5. Thermal efficiency depending on the ambient temperature

The above graph (Fig. 5) represents the thermal efficiency of the cell depending on the ambient temperature. The efficiency drops when the ambient temperature increases.

2.4. Technical analysis of a photovoltaic system with water cooling system and one without cooling system

Technical analysis is performed to observe if is profitable an additional investment for a water cooling system that is designed to absorb heat from solar panels, thereby improving the efficiency of the photovoltaic system.

Initial data for the analysis performed are as follows:

- The PV system consists of 13 polycrystalline photovoltaic panels of 225 W (the nominal power is P=3 kW)
- Electrical efficiency of a panel is about 14%
- *Nominal Operating Cell Temperature* (NOCT) is 45°C
- Thermal coefficient of power losses is c_{tp}= 0.5%/ °C
- Water inlet temperature is about T_i = 10 °C
- The PV system is located in Bucharest
- Inclination of the panels is 15 °, facing south

Meteorological data for Bucharest were taken from the online database of Photovoltaic Geographical Information System (PVGIS).

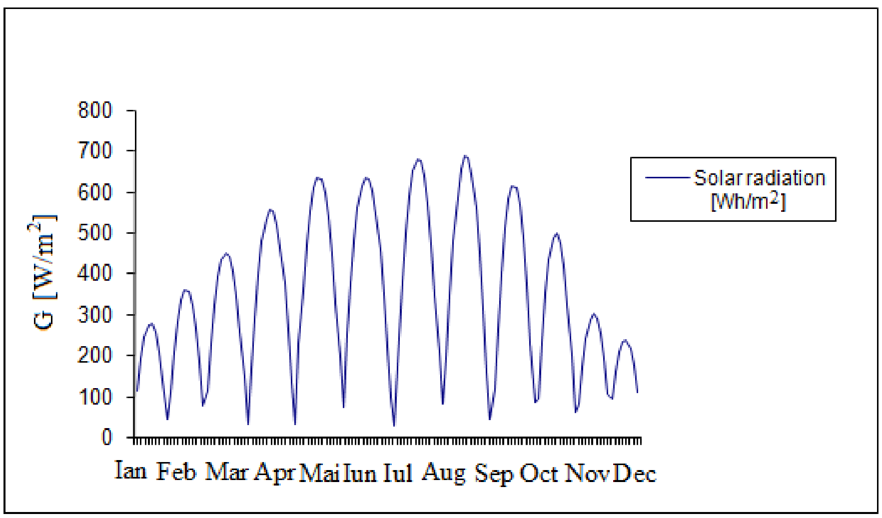

Fig.6. Average daily solar radiation for each month in Bucharest

The average daily solar radiation for each month in Bucharest is represented in Fig. 6.

If photovoltaic modules are heated they produce less electricity, so they must be cooled and maintained at a temperature about 25 to 30 °C.

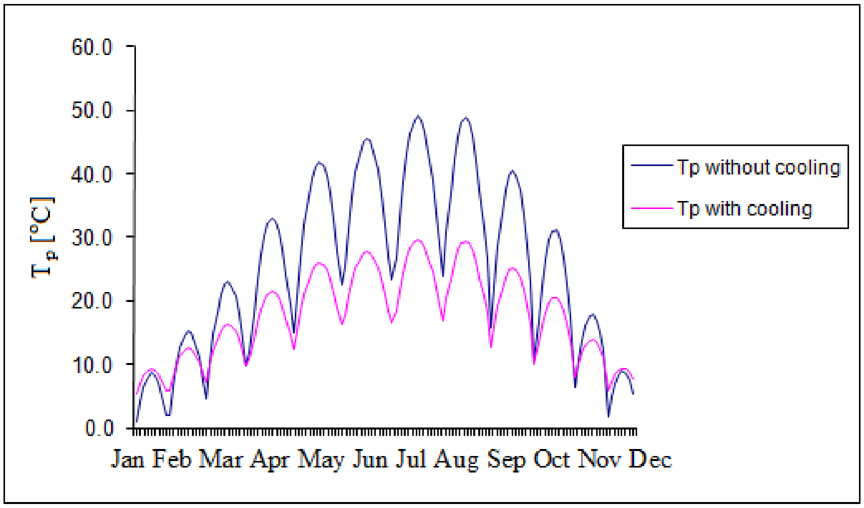

Fig.7. Graphical representation of the photovoltaic cell temperature for the two cases

The photovoltaic cell temperature for the two cases: with cooling and without cooling is represented in Fig. 7. It can be observe that when they are not cooled the temperature reaches up to 50 °C , and when they are cooled the temperature reaches up to 25-30 °C, which is the ideal temperature for a normal operation.

As much their temperature is lower their efficiency is higher and the produced energy is increased. That can be observe in Fig. 8.

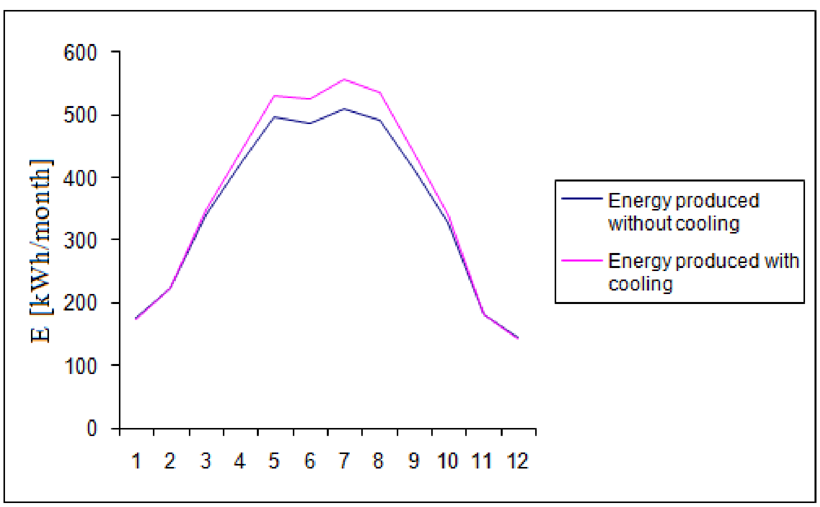

Fig.8. Graphical representation of produced electricity for the two cases

Annual energy produced by the PV system without cooling system is 4,208 MWh / year, and by the PV system with cooling system is 4,442 MWh / year.

For cooling the photovoltaic panels is required a circulation pump to ensure the transport of cold water from the tank to the panels and hot water from the panels back into the tank. Electrical consumption of the circulation pump is about 50 kWh / year.

Thereby it can be seen that the additional energy obtained is about 200 kWh / year.

3. Conclusions

From the work done and presented the main conclusions drawn are:

- ➔ An increase of the operating temperature of the panel affects the solar cell efficiency of the system.
- ➔ The physical properties of the heat exchanger in the water cooled photovoltaic can alter greatly the efficiency of the system. Using the spreadsheet developed, various physical parameters of the system were tested in order to see the effect on the efficiency of the PV.
- ➔ Apart from the properties of the heat exchanger, the inlet water temperature as well as the ambient temperature plays an important role in the system's operation. As it was diagrammatically shown in the parametric analysis chapter, when the water inlet temperature is low the thermal efficiency is high. Consequently, when the inlet temperature of the coolant gets higher, the efficiency decrease. A similar result stands for the ambient temperature case.

The power gained from a cooled panel is higher than the one from a conventional system, and the additional energy obtained is higher than the cooling energy required, so an additional investment is profitable for the Passive House located inside the Polytechnic University of Bucharest.

Nomenclature

q - the heat per length in the fluid direction y

σ - the Stefan's Boltzmann's constant

$P(T_s)$ - the electrical power per area that can be drawn from the solar cell under the total irradiance G.

G – total irradiance

m – transport mass

q_f - the heat per length that it is bought to the tube from the fin

R_S - the radiation from the solar cell
α - absorbance
ε - emissivity
ρ - reflectivity
τ - transmittance
λ - conductivity
U'_{Aa} - the loss factor from the absorber when the loss through the solar cells is accounted for
U_{AF} - the conductance between the absorber and the fluid
U_{Fa} - the conductance between the fluid and the ambience
U_{SA} - the conductance between the solar cell and the absorber
U_{Aa} - the sum of edge and bottom losses due to conductance and convection
U''_{Aa} – the modified loss factor
F_R - is the radiation loss factor
T - temperature of the fluid
T_a - temperature of the ambience
T_A - temperature of the absorber
T_{Af} - temperature of the absorber on the fin
T_c - temperature of the cover (K)
T_i - inlet fluid temperature (K)
T_L - outlet fluid temperature (K)
T_S - temperature of the solar cell (K)
F_f - fin factor
$F(T)$ – collector's efficiency factor
$F_R(T)$ - effective radiation loss factor
U_L - total conductive loss factor
η_A - thermal efficiency
$F'(T_a)$ - differentiated collector efficiency factor
$F'_R(T_a)$ - differentiated effective radiation loss factor
T_{af} - the x-dependent temperature of the absorber on the fin

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