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Analysis of an innovative water-cooling solution for photovoltaic-thermal systems

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Abstract. The research is focused on realizing a comparative analysis regarding the parameters of an active water-cooling solution for improving the efficiency of monocrystalline silicon photovoltaic (PV) panels. The efficiency of the photovoltaic panels is dependent on the climatic conditions, varying especially with the change of the intensity of the solar radiation and of the operating temperature. The cooling of the photovoltaic panels is a viable solution for both fixed and variable positions of the system. Numerical modelling was carried out on a photovoltaic panel integrated into the façade of a buildings. The water-cooling solution consist in using a water film heat exchanger attached on the backside of the PV panel. The parameters of the heat agent analysed were the temperature, velocity and width of the water film. The optimal water film heat exchanger solution was obtained for a thickness of 3 mm of water film, a velocity of 0.01 m/s and an operating temperature of 20 °C. In this case, the thermal power extracted by the film exchanger reaches values of 140.8 W, with an overall heat exchange coefficient of 48.6 $W/m^2 \cdot K$. During the study, the global heat transfer coefficient and the raise off efficiency is determined for each case.

1. Introduction

There are studies in the literature on the dependence between conversion efficiency and operating temperature of photovoltaic (PV) panels [1, 2]. A linear inversely proportional variation between temperature and efficiency has been proved [3]. The reduction in efficiency can be considered to be about 0.3% ... 0.5% for each degree of temperature rise above 25 °C (known as STC temperature). Skoplaki E. et al. present different methods and equations for calculating the dependence between conversion efficiency and photovoltaic cell temperature [4].

Efficiency can be increased by reducing the operating temperature of the photovoltaic cell, as it is more difficult to control or modify other important parameters, such as solar radiation or tilt of the surface. For example, in the particular case of placing photovoltaic panels on the facades of the building, which are vertical and fixed surfaces, the direction and intensity of solar radiation are uncontrollable values.

Different strategies for cooling photovoltaic panels are presented in the literature and the most used solutions are the use of air cooling [5, 6] and water cooling [7, 8]. Almost every solution used for photovoltaic cooling provides the extracted heat for other uses, so that the recovery time is shorter than that of ordinary photovoltaic systems.

IOP Conf. Series: Earth and Environmental Science **664** (2021) 012025 doi:10.1088/1755-1315/664/1/012025

A possibility for cooling photovoltaic panels by using water as a heat transfer agent is presented in [9]. This study presents a hybrid photovoltaic panel. Behind the panel is attached a functional graded material (FGM) with a coil inside it for water circulation. This circuit has the role of extracting heat from the PV panel and also from the solar collector. This type of systems is known in the literature as hybrid photovoltaic or PV/T photovoltaic-thermal solar collector [9, 10].

A widespread solution to improve conversion efficiency consists in integration of photovoltaic (PV) panels in building facades, a technology known as integrated photovoltaic building (BIPV). Photovoltaic panels replace areas of exterior or interior windows, creating active walls and active cold or warm facades [11].

By using the BIPV technique, the facade of buildings can be used, taking into account that in crowded areas, buildings have an important tendency to grow vertically [12]. At the same time, it is difficult to obtain a sufficient horizontal surface on building for the placement of photovoltaic panels.

2. Problem description

The aim of the study is to determine the energy efficiency of a PV panel under water cooling conditions, using a water film heat exchanger, located at the back of PV. The conversion efficiency of the photovoltaic panel is compared for the various operating temperatures resulted.

The operating temperature of the photovoltaic panel is evaluated according to the velocity and temperature of the heat transfer agent in the inlet section of the water film heat exchanger and its thickness. A photovoltaic panel with an area of 0.25 m^2 (0.5 m x 0.5 m) integrated in front of a building is analyzed.

2.1. Water film heat exchanger

The water film heat exchanger is an assembly consisting of two metal plates, with a small space between them, through which circulates the heat transfer agent - water [7, 8]. The heat exchanger allows the extraction of thermal energy from the rear area of the photovoltaic panel. The contact area between it and the photovoltaic panel is made of copper, a material with a high thermal conductivity.

The use of water as a cooling agent for photovoltaic panels is a solution analyzed in different studies [9, 13, 8]. The hybrid photovoltaic panels studied in literature have attached a water coil with the role of both cooling the PV panel and solar collector. Most water-cooling techniques are placed in the category of active cooling solutions and are superior to air cooling, but more expensive. Taking into account the positive existing results, during the implementation of the present project, an innovative technology of water cooling will be tested, by using a water film heat exchanger attached to PV. The proposed technology presents qualitative and quantitative advantages over the ones analyzed in literature: the uniformity of the heat flow extracted and the reduction of the water flow requirement for cooling, due to the low speeds and the reduced dimensions of the water film created [14].

The dimensions of the water film heat exchanger are:

$$l \cdot h \cdot g = 0{,}5m \cdot 0{,}5m \cdot (0{,}001...0{,}01)m \qquad (1)$$

where, l – length of the water film heat exchanger [m];
h – height of the water film heat exchanger [m];
g – width of the water film [m].

The input data for the calculation are:

- position of PV panel: - vertical, on the façade of the building;
- constant intensity of solar radiation: G_{med} = 500 W/m^2;
- dimensions of the water film heat exchanger: 0,5 m x 0,5 m;
- width of the water film: g = 3...10 mm;
- inlet temperature of the heat transfer agent: from 20 °C to 30 °C, with 1 °C steps;
- PV panel solar radiation absorption coefficient, α = 0,8 [15, 16];
- inlet velocity of the heat transfer agent: variable: 0,001 m/s, 0,002 m/s, 0,003 m/s, 0,004 m/s, 0,005 m/s and 0,01 m/s, according to the following flow rates: 0,09 l/min, 0,18 l/min, 0,27 l/min, 0,36 l/min, 0,45 l/min and 0,9 l/min.

IOP Conf. Series: Earth and Environmental Science **664** (2021) 012025 doi:10.1088/1755-1315/664/1/012025

Parameters analyzed:
- t_p – average operating temperature of the photovoltaic panel;
- η – efficiency of PV panel.

3. Numerical approach

The numerical study on the variation of the average operating temperature of the photovoltaic panel is performed using the ANSYS-Fluent software. The geometry and discretization of the computing domain is performed within the ANSYS platform, by using the Design-Meshing and Design-Modeler programs. The simulation of solar radiation is performed using the Solar Ray Tracing model of the Fluent program. The sketch of the model studied in the paper is presented in Figure 1.

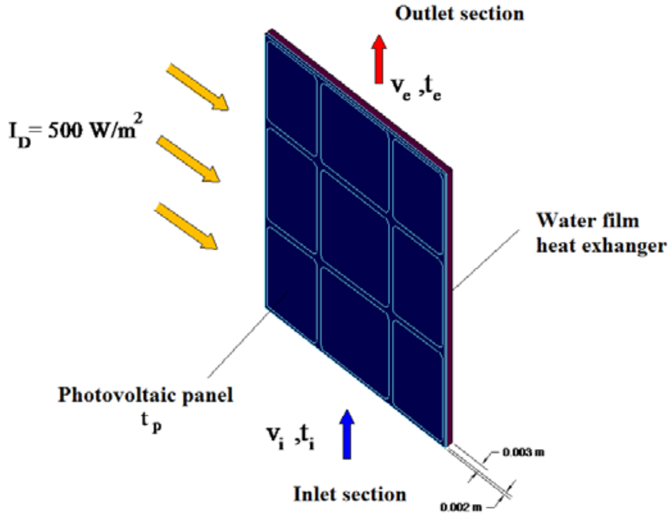

Figure 1. The PV panel with water film heat exchanger studied numerically

where, G_{med} – the intensity of solar radiation [W/m^2];
t_i, t_e – heat transfer agent temperatures in the inlet and outlet section [°C];
v_i, v_e – heat transfer agent velocities in the inlet and outlet section [m/s];
t_p – average temperature of the photovoltaic panel [°C].

During the simulations, different configurations and operating parameters of the water film heat exchanger were analyzed, by varying the thickness of the water film, temperature and flow.

4. Results

4.1. The influence of the velocity of the water in the heat exchanger

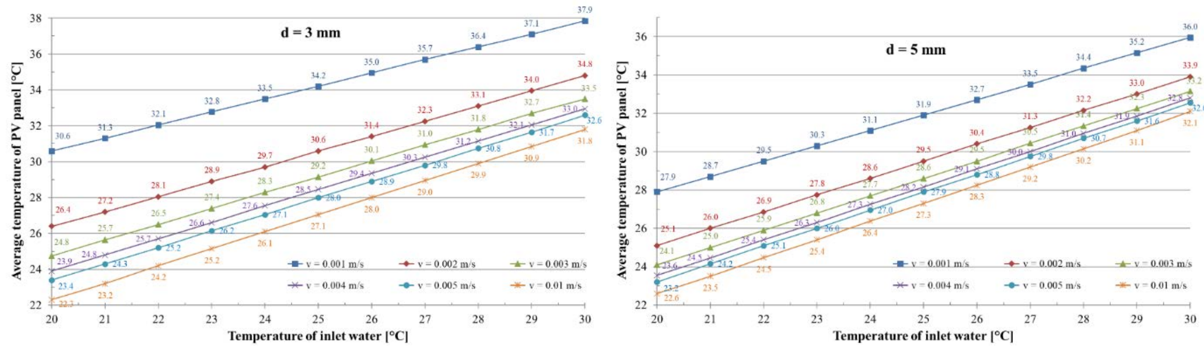

Figure 2. Average variation of the operating temperature of PV panel as a function of velocity and inlet temperature of the heat transfer agent for a) d = 3 mm and b) d = 5 mm

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Figure 2 and Figure 3 show the results obtained for the simulations at constant thicknesses of the water film, at variable temperatures and velocities of the water in the inlet section.

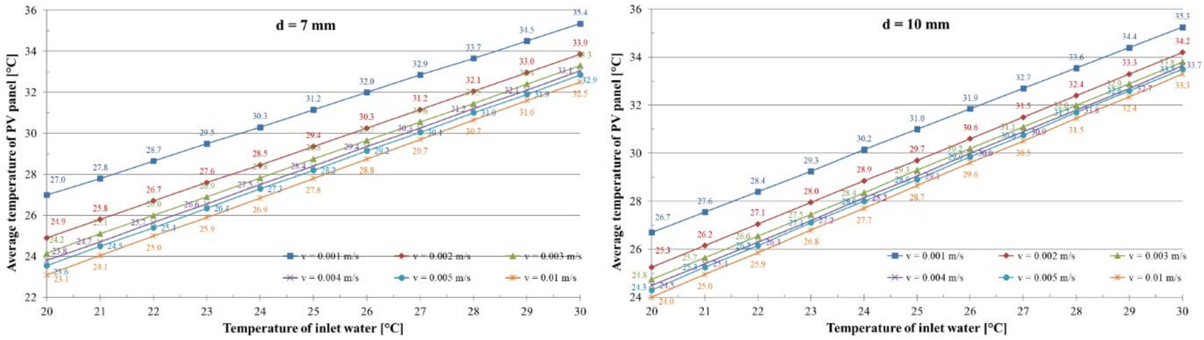

Figure 3. Average variation of the operating temperature of PV panel as a function of velocity and inlet temperature of the heat transfer agent for a) d = 7 mm and b) d = 10 mm

4.2. The influence of water film thickness

Figures 4 - 6 show the results obtained for simulations at constant velocities of water in the inlet section, for variable temperatures and the four thicknesses of the water film.

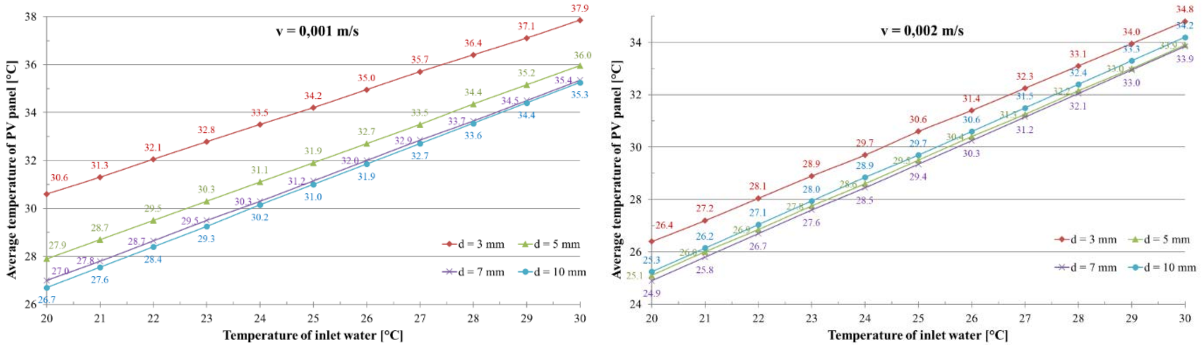

Figure 4. Variation of average operating temperature of PV panel as a function of water film thickness and heat transfer agent temperature at velocity of a) v_i = 0,001 m/s and b) v_i = 0,002 m/s

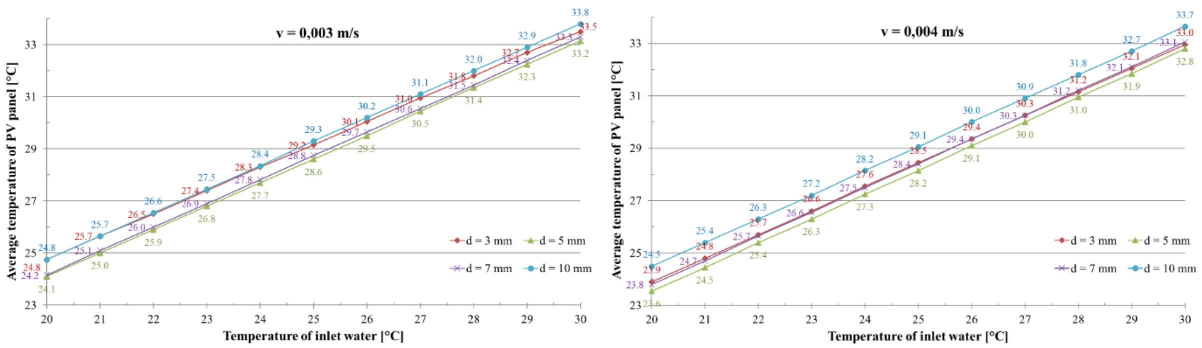

Figure 5. Variation of average operating temperature of PV panel as a function of water film thickness and heat transfer agent temperature at velocity of a) v_i = 0,003 m/s and b) v_i = 0,004 m/s

It can be seen that the cooling effect of the photovoltaic panel is directly proportional to the velocity of water entering the water film heat exchanger and inversely proportional to its temperature, Figures 4 - 6. Also, the temperature of the photovoltaic panel has a significant decrease when the water velocity

IOP Conf. Series: Earth and Environmental Science **664** (2021) 012025 doi:10.1088/1755-1315/664/1/012025

in the inlet section is increased from 0.001 m/s to 0.002 m/s, with values between 4.2 ... 3.1 °C, for d = 3 mm, respectively 1.4 ... 1.1 ° C, for d = 10 mm, being also dependent on the water inlet temperature. This effect is diminished as the inlet velocity increases, so that the temperature difference between the speed of 0.005 m/s and the double value of 0.01 m/s is about 1 ° C.

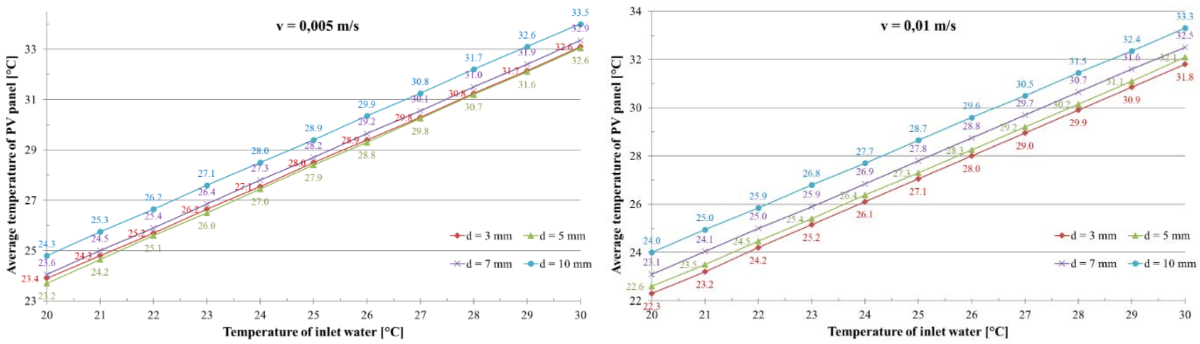

Figure 6. Variation of average operating temperature of PV panel as a function of water film thickness and heat transfer agent temperature at velocity of a) v_i = 0,005 m/s and b) v_i = 0,01 m/s

4.3. *The global heat transfer coefficient for the studied configurations*

For all the configurations studied, the thermal energy extracted and the global heat transfer coefficient of the water film heat exchanger were determined. The calculation was performed taking into account the average parameters of water, air and photovoltaic panel. The results obtained are centralized in graphical form, in Figures 7 - 9.

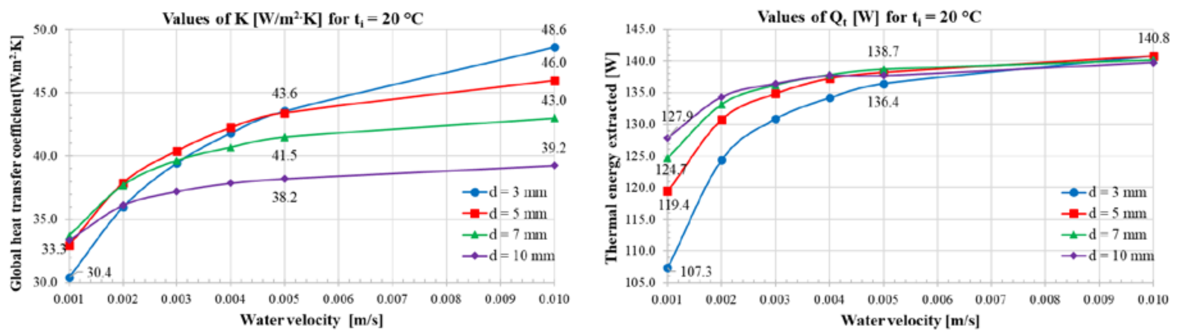

Figure 7. Values of the (a) global heat transfer coefficient – K [W/m^2·K] and of the (b) thermal energy extracted – Q [W], depending on velocity, at constant temperature t_i = 20 °C

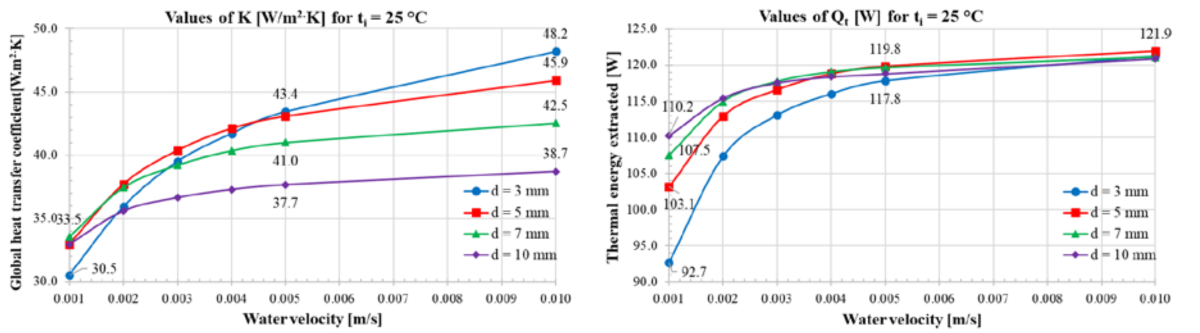

Figure 8. Values of the global heat transfer coefficient – K [W/m^2·K] and of the thermal energy extracted – Q [W], depending on velocity, at constant temperature t_i = 25 °C

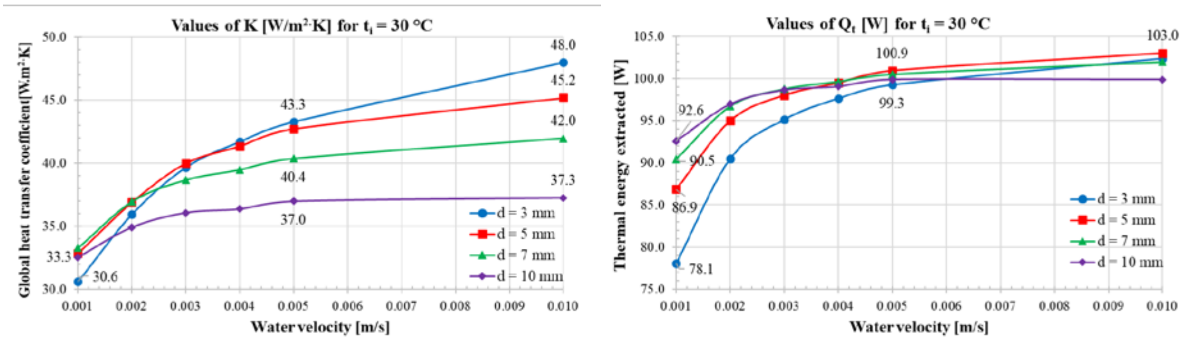

Figure 9. Values of the global heat transfer coefficient – K [W/m^2·K] and of the thermal energy extracted – Q [W], depending on velocity, at constant temperature t_i = 30 °C

4.4. The efficiency of the photovoltaic panel with water cooling

The average temperature of the photovoltaic panel, in the base case (without using the water film heat exchanger), reaches values of about 75 °C, in the same conditions of solar radiation [5]. Therefore, the photovoltaic conversion efficiency can be determined for the base case and for the cases when the temperatures are lower due to use the water film changer. In order to improve the working temperature of the photovoltaic panel and including the conversion efficiency, it is cooled to temperatures close to the operating one under standard conditions, respectively 25 °C.

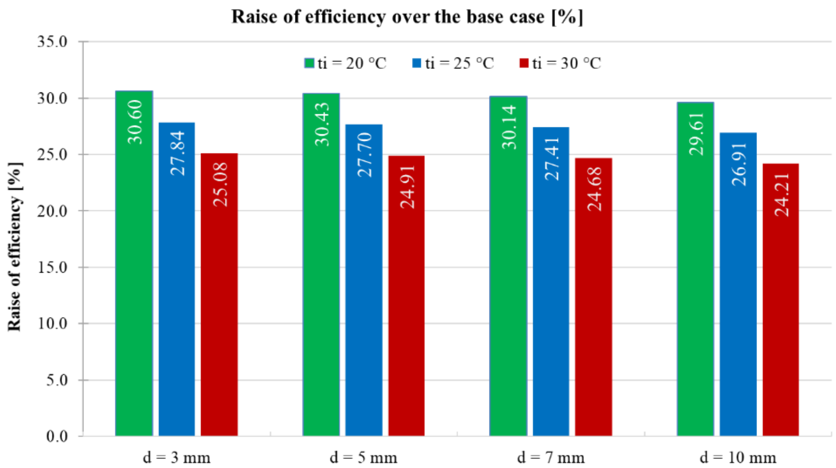

Figure 10. The increase of the efficiency of water-cooled PV panel compared to the base case, for different water inlet temperatures and water film thicknesses

Figure 10 shows the efficiency increases compared to the base case, obtained for the various thicknesses of the water film and inlet temperatures.

The influence of the panel temperature on its conversion efficiency is presented numerically in Tables 1 - 3, for the studied cases, for the water inlet temperature of 20 °C, 25 °C and 30 °C.

In Table 1 it can be observed that by using cooling with water at 20 °C it is possible to obtain a power increase between 25.78% and 30.60%, compared to the case.

Table 1. The increase of the efficiency of PV panel depending on the water film thickness and inlet velocity for t_i = 20 °C

Case	v_{water} [m/s]	q [l/min]	t_p [°C]	[%] of P_N	η [%]	P_{elspec} [W/m²]	P_{el} [W]	Raise [%]
Base	-	-	75,0	77,5	11,37	56,9	14,22	-
***d* = 3 mm**	0,001	0,09	30,6	97,5	14,30	71,6	17,89	25,78
	0,002	0,18	26,4	99,4	14,58	72,9	18,23	28,22
	0,003	0,27	24,8	100,1	14,69	73,5	18,37	29,18
	0,004	0,36	23,9	100,5	14,74	73,8	18,44	29,67
	0,005	0,45	23,4	100,7	14,78	73,9	18,48	29,96
	0,01	**0,90**	**22,3**	**101,2**	**14,85**	**74,3**	**18,57**	**30,60**
***d* = 5 mm**	0,001	0,15	27,9	98,7	14,48	72,4	18,11	27,35
	0,002	0,30	25,1	100,0	14,66	73,4	18,34	28,97
	0,003	0,45	24,1	100,4	14,73	73,7	18,42	29,55
	0,004	0,60	23,6	100,7	14,77	73,9	18,47	29,87
	0,005	0,75	23,2	100,8	14,79	74,0	18,50	30,08
	0,01	1,50	22,6	101,1	14,83	74,2	18,55	30,43
***d* = 7 mm**	0,001	0,21	27,0	99,1	14,54	72,7	18,18	27,87
	0,002	0,42	24,9	100,0	14,68	73,4	18,36	29,09
	0,003	0,63	24,2	100,4	14,73	73,7	18,42	29,53
	0,004	0,84	23,8	100,5	14,75	73,8	18,45	29,73
	0,005	1,05	23,6	100,7	14,77	73,9	18,47	29,87
	0,01	2,10	23,1	100,9	14,80	74,0	18,51	30,14
***d* = 10 mm**	0,001	0,30	26,7	99,2	14,56	72,8	18,21	28,05
	0,002	0,60	25,3	99,9	14,65	73,3	18,33	28,89
	0,003	0,90	24,8	100,1	14,69	73,5	18,37	29,18
	0,004	1,20	24,5	100,2	14,70	73,6	18,39	29,32
	0,005	1,50	24,3	100,3	14,72	73,6	18,41	29,44
	0,01	3,00	24,0	100,5	14,74	73,7	18,43	29,61
Nominal (STC)	-	-	25	100	14,67	73,4	18,35	29,03

For water inlet temperatures of 25 °C and 30 °C, the power increase is between 23.69 ... 27.84% and 21.57 ... 25.08%, respectively. The decrease of the conversion efficiency of the photovoltaic panel considered in the calculation is -0.45%/°C, at temperatures higher than 25 °C.

Table 2. The increase of the efficiency of PV panel depending on the water film thickness and inlet velocity for t_i = 25 °C

Case	v_{water} [m/s]	q [l/min]	t_p [°C]	[%] of P_N	η [%]	P_{elspec} [W/m²]	P_{el} [W]	Raise [%]
Base	-	-	75,0	77,5	11,37	56,9	14,22	-
***d* = 3 mm**	0,001	0,09	34,2	95,9	14,06	70,4	17,59	23,69
	0,002	0,18	30,6	97,5	14,30	71,6	17,89	25,78
	0,003	0,27	29,2	98,1	14,40	72,0	18,01	26,62
	0,004	0,36	28,5	98,4	14,44	72,3	18,07	27,03
	0,005	0,45	28,0	98,7	14,47	72,4	18,10	27,29
	0,01	**0,90**	**27,1**	**99,1**	**14,53**	**72,7**	**18,18**	**27,84**
***d* = 5 mm**	0,001	0,15	31,5	97,1	14,24	71,3	17,81	25,26
	0,002	0,30	29,5	98,0	14,37	71,9	17,98	26,42
	0,003	0,45	28,6	98,4	14,43	72,2	18,05	26,94
	0,004	0,60	28,2	98,6	14,46	72,4	18,09	27,20
	0,005	0,75	27,9	98,7	14,48	72,4	18,11	27,35
	0,01	1,50	27,3	99,0	14,52	72,6	18,16	27,70
***d* = 7 mm**	0,001	0,21	31,2	97,2	14,26	71,4	17,84	25,46
	0,002	0,42	29,4	98,0	14,38	72,0	17,99	26,51
	0,003	0,63	28,8	98,3	14,42	72,2	18,04	26,85
	0,004	0,84	28,4	98,5	14,45	72,3	18,07	27,06
	0,005	1,05	28,2	98,6	14,46	72,3	18,09	27,17
	0,01	2,10	27,8	98,7	14,49	72,5	18,12	27,41
***d* = 10 mm**	0,001	0,30	31,0	97,3	14,27	71,4	17,85	25,55
	0,002	0,60	29,7	97,9	14,36	71,8	17,96	26,30
	0,003	0,90	29,3	98,1	14,39	72,0	17,99	26,54
	0,004	1,20	29,1	98,2	14,40	72,1	18,02	26,68
	0,005	1,50	28,9	98,2	14,41	72,1	18,03	26,77
	0,01	3,00	28,7	98,4	14,43	72,2	18,05	26,91
Nominal (STC)	-	-	25	100	14,67	73,4	18,35	29,03

Table 3. The increase of the efficiency of PV panel depending on the water film thickness and inlet velocity for t_i = 30 °C

Case	v_{water} [m/s]	q [l/min]	t_p [°C]	[%] of P_N	η [%]	P_{elspec} [W/m²]	P_{el} [W]	Raise [%]
Base	-	-	75,0	77,5	11,37	56,9	14,22	-
***d* = 3 mm**	0,001	0,09	37,9	94,2	13,82	69,2	17,29	21,57
	0,002	0,18	34,8	95,6	14,02	70,2	17,54	23,34
	0,003	0,27	33,5	96,2	14,11	70,6	17,65	24,10
	0,004	0,36	33,0	96,4	14,15	70,8	17,69	24,42
	0,005	0,45	32,6	96,6	14,17	70,9	17,72	24,62
	0,01	**0,90**	**31,8**	**96,9**	**14,22**	**71,2**	**17,79**	**25,08**
***d* = 5 mm**	0,001	0,15	36,0	95,1	13,95	69,8	17,45	22,67
	0,002	0,30	33,9	96,0	14,08	70,5	17,62	23,86
	0,003	0,45	33,2	96,3	14,13	70,7	17,68	24,30
	0,004	0,60	32,8	96,5	14,16	70,8	17,71	24,50
	0,005	0,75	32,6	96,6	14,17	70,9	17,73	24,65
	0,01	1,50	32,1	96,8	14,20	71,1	17,76	24,91
***d* = 7 mm**	0,001	0,21	35,4	95,3	13,99	70,0	17,50	23,02
	0,002	0,42	33,9	96,0	14,09	70,5	17,62	23,89
	0,003	0,63	33,3	96,3	14,12	70,7	17,66	24,21
	0,004	0,84	33,1	96,4	14,14	70,7	17,69	24,36
	0,005	1,05	32,9	96,5	14,15	70,8	17,70	24,47
	0,01	2,10	32,5	96,6	14,17	70,9	17,73	24,68
***d* = 10 mm**	0,001	0,30	35,3	95,4	13,99	70,0	17,50	23,08
	0,002	0,60	34,2	95,9	14,06	70,4	17,59	23,69
	0,003	0,90	33,8	96,0	14,09	70,5	17,62	23,92
	0,004	1,20	33,7	96,1	14,10	70,5	17,64	24,01
	0,005	1,50	33,5	96,2	14,11	70,6	17,65	24,10
	0,01	3,00	33,3	96,3	14,12	70,7	17,66	24,21
Nominal (STC)	-	-	25	100	14,67	73,4	18,35	29,03

The meaning of the terms in Tables 1 - 3 is as follows:
P_N – electrical power produced at 25 °C [W];
$P_{elespec}$ – specific electrical power [W/m²];
S_p – the surface of the photovoltaic panel [m²];
P_{el} – the electrical power produced by the studied panel [W].

5. Conclusions

Cooling photovoltaic panels is an advantageous solution to improve their conversion efficiency. Reducing the operating temperature by using water as a heat transfer agent has multiple advantages. Thus, the cold water from the supply system can be used, being a cheap energy source and with optimal parameters for extracting the surplus energy stored in the mass of the photovoltaic panel. By using a water film heat exchanger and storing or harnessing the extracted thermal energy, the energy efficiency of the entire system, evaluated globally, is superior to the efficiency of the photovoltaic system itself.

The numerical modeling aimed at determining the most advantageous solution for cooling the photovoltaic panel with water, using a water film heat exchanger. The variables studied for the water film heat exchanger are the thickness of the water film, the velocity and the temperature of the water in the inlet section. The optimal solution was obtained for a thickness of 3 mm of water film, a velocity of 0.01 m / s and an operating temperature of 20 °C. In this case, the thermal power extracted by the water film heat exchanger reaches values of 140.8 W, with an overall heat exchange coefficient of 48.6 $W/m^2 \cdot K$. Under the same conditions, the temperature of the photovoltaic panel is maintained at about 22.3 °C, and the efficiency is 30.6% higher than in the base case. The most disadvantageous case is also recorded for the width of 3 mm of the water film, the velocity of 0.001 m/s and the water temperature of 30 °C, when the temperature of the photovoltaic panel is reduced only to 37.9 °C.

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