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EXPERIMENTAL CORRELATION OF THE CONVECTIVE HEAT TRANSFER COEFFICIENT FOR PV MODULE SURFACES

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In this paper, a correlation for the convective heat transfer coefficient from the surfaces of photovoltaic (PV) modules is proposed. This correlation was established by experimentally measuring the temperature of PV modules under outdoor conditions, specifically using an open rack-mount setup in which the modules are placed on a freestanding frame and exposed to the surrounding environment. The coefficients of the assumed power-law correlation between the convective heat transfer coefficient and the magnitude of the local wind velocity are determined using the particle swarm optimization (PSO) algorithm and the least-squares method, and the results are compared with measured PV module temperatures calculated using a transient thermal model. Finally, the proposed correlation is compared with similar correlations of this type. While some correlations for the convective heat transfer coefficient yield an average difference of nearly 10 °C between the calculated and measured temperatures of the PV module, the proposed correlation allows the PV module's temperature to be estimated with a deviation of no more than 3 °C.

1. INTRODUCTION

It is well known that the efficiency of photovoltaic (PV) modules depends significantly on temperature [1–6]. For analyzing PV module performance (primarily calculating the expected power output under specific ambient conditions), it is essential to understand how the PV module's temperature depends on ambient conditions, in addition to its construction parameters [7,8]. Ambient conditions include ambient temperature, wind velocity and direction, and solar radiation intensity. To this end, a large number of stationary and transient thermal models have been developed, some of which are obtained experimentally, while others are based on the energy balance law between the received solar radiation energy, the portion of this energy converted into electrical energy in the PV module, and the released thermal energy from the PV module by convection and radiation [1,3,9–12].

Table 1
The most commonly used correlations for calculating the convective heat transfer coefficient from the surfaces of PV module

Correlation	Note	Eq.	Reference
$h_w = 5.7 + 3.8v_w$	Flat plate, $v_w \leq 5$ m/s, smooth surface, parallel flow.	(1)	McAdams [14]
$h_w = 2.8 + 3v_w$	Modified correlation (1), the effect of radiation and natural convection is excluded, $v_w \leq$ 5 m/s.	(2)	Wattmuff et al. [15]
$h_w = 8.55 + 2.56v_w$	A flat plate tilted at different angles relative to the horizontal, $v_w \leq 5$ m/s, rear surface thermally insulated.	(3)	Test et al. [16]
$h_w = 6.5 + 3.3v_w$	Heated surface installed directly on the pitched roof of a residential-sized building, $v_w \leq 6$ m/s, wind flow parallel to plate.	(4)	Sharples and Charlesworth [17]
$h_w = 10.03 + 4.687v_w$	Heated square plate (0.368 m^2), $v_w \leq 5$ m/s.	(5)	Kumar et al. [18]
$h_w = 6.90 + 3.87v_w$	Unglazed horizontally mounted flat plate collector of size 0.925 × 0.865 m^2, $v_w \leq 1.12$ m/s, rear surface thermally insulated.	(6)	Kumar and Mullick [19]
$h_w = 5.8 + 3.95v_w$	Flat plate, $v_w \leq 5$ m/s, smooth surface, parallel flow.	(7)	Nusselt and Jürges [20]
$h_w = 7.11v_w^{0.775}$	Flat plate, $5 < v_w < 24$ m/s, smooth surface, parallel flow.	(8)	Jürges [21]
$h_w = 7.2v_w^{0.78}$	Correlation obtained on the basis of data from [16,17], $v_w > 5$ m/s, smooth flat surface.	(9)	McAdams [22]

The heat released from the surfaces of PV modules by convection is about 3-4 times greater than the heat released by radiation [13]. Consequently, accurately estimating the temperature of PV modules depends on the precise value of the convective heat transfer coefficient from the module surface (h_w). The literature contains numerous correlations for determining this coefficient. Some are quite simple – representing an average for both sides of the PV module (windward and leeward) and considering only wind velocity (v_w) [14–24], while others are more complex, taking into account not only wind velocity but also dust deposition, the angle of attack of the wind relative to the PV module, the length of the PV module along the direction of the wind, and whether the flow is laminar, turbulent, or somewhere in between [9,10,17,25].

Table 1 summarizes some of the correlations most used to determine the coefficient h_w, along with the conditions under which they are applied. The table includes only correlations related to PV modules mounted on the ground (not on rooftops) without concentrators (one-sun applications). It is evident that the correlations in Table 1 yield different results for the same wind velocity. This discrepancy arises because they are determined for different flat-surface dimensions and materials (copper, aluminum, wood) under various operational conditions (mostly tested in wind tunnels) and then applied to PV modules. Additionally, some of these correlations include both radiation and convection [19]. For example, correlation (1) was obtained based on measurements for a copper plate with dimensions 0.5 m × 0.5 m and parallel airflow along it. It is assumed that this correlation includes the contribution from heat released by radiation. Correlation (2) was obtained in a wind tunnel, and it is a modified version of correlation (1), where the contribution from radiation has been excluded. Duffie and Beckman [26] expressed doubts about the accuracy of correlation (2) for plates with characteristic lengths different from 0.5 m. Correlation (3) was obtained for a sandwich panel with dimensions 1.22 m × 0.813 m × 0.2 m (length ×

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width × thickness). The front and rear surfaces of this panel are copper plates with a heater and epoxy between them. Correlation (4) was obtained based on measurements from a solar collector with dimensions 1.81 m × 0.89 m mounted on a roof. Heat transfer from the rear surface of the collector was neglected because this surface was thermally insulated. Kumar et al. [18] derived correlation (5) based on measurements conducted on a box-type solar cooker.

None of the correlations in Table 1 has been established based on measurements from PV modules of modern dimensions and characteristics mounted on a frame on the ground in outdoor conditions. It is not difficult to conclude that the results obtained using these correlations will have some degree of error.

In this study, the correlation for the convective heat transfer coefficient from the PV module surfaces was indirectly determined based on the measured temperature of the polycrystalline PV module and ambient conditions. The resulting correlation applies to crystalline silicon (c-Si) PV modules of typical dimensions in outdoor conditions, which is a very common method of PV module deployment.

To determine the coefficients for the assumed dependency $h_w = f(v_w)$, the PSO algorithm and the least squares method are used. To the best of the authors' knowledge, no such procedure exists in the literature. A similar procedure was conducted in [13], but for PV modules with concentrators (CPV devices under mid-concentration), while in [19], the coefficient h_w was determined for the upper surface of an aluminum plate of dimension 925 mm × 865 mm, with its back surface thermally insulated.

2. METHODOLOGY FOR DETERMINING CONVECTIVE HEAT TRANSFER COEFFICIENT

The transient energy balance equation between the received solar radiation energy, the portion of this energy converted into electrical energy in the PV module, and the released thermal energy from the PV module by convection and radiation is expressed as follows [1]:

$$C_{PV}\frac{\mathrm{d}T_{PV}}{\mathrm{d}t} - q_{sun} + q_{conv} + q_{rad} + P_{el} = 0, \quad (10)$$

where T_{PV} [K] is the temperature of the PV module, C_{PV} [J/K] is the PV module thermal capacity, q_{sun} [W] is the net amount of incoming solar flux on the PV module, q_{conv} [W] is the net amount of convection heat transfer, q_{rad} [W] is the net amount of radiation heat transfer, and P_{el} [W] is the electric output.

The thermal capacity C_{PV} represents the PV module thermal lag. The value of C_{PV} in this paper is 22800 J/K [1].

The terms of eq. (10) can be calculated in the following manner:

$$q_{sun} = AG(\tau\alpha) \quad (11)$$

$$q_{rad} = A(h_{rad,f}(T_{PV} - T_{sky}) + h_{rad,b}(T_{PV} - T_{gr})) \quad (12)$$

$$h_{rad,f} = \sigma_{SB}(T_{PV}^2 + T_{sky}^2)\frac{(T_{PV}+T_{sky})\varepsilon_b(1+\cos(\pi+\delta))}{2} + \\ +\sigma_{SB}(T_{PV}^2 + T_{gr}^2)\frac{(T_{PV}+T_{gr})\varepsilon_b(1-\cos(\pi+\delta))}{2}, \quad (13)$$

$$h_{rad,b} = \sigma_{SB}(T_{PV}^2 + T_{sky}^2)\frac{(T_{PV}+T_{sky})\varepsilon_b(1+\cos(\pi-\delta))}{2} + \\ +\sigma_{SB}(T_{PV}^2 + T_{gr}^2)\frac{(T_{PV}+T_{gr})\varepsilon_b(1-\cos(\pi-\delta))}{2}, \quad (14)$$

$$q_{conv} = Ah_w(T_{PV} - T_a), \quad (15)$$

$$T_{sky} = 0.0552 T_a^{1.5}, \quad (16)$$

$$T_{gr} = T_a, \quad (17)$$

$$P_{el} = \eta_{T_{ref}} AG(\tau\alpha)(1 - \beta_{ref}(T_{PV} - T_{ref})). \quad (18)$$

In eqs. (11) – (18), the variables are defined as follows: G [W/m^2] is the solar irradiance in; A [m^2] is the PV module area; $\tau\alpha$ is the coefficient of transmission/absorption for the front surface of PV module ($\tau\alpha$ = 0.855 according to [1]); $h_{rad,b}$ and $h_{rad,f}$ [W/(m^2·K)] are the radiation heat transfer coefficient for the back and front surface of PV module to the environment, respectively; ε_b and ε_f are the coefficients of emissivity for the back and the front surface of PV module, respectively; T_{gr} and T_{sky} [K] are the ground and the sky temperatures, respectively; δ [degrees (°)] is the tilt angle of PV module relative to the horizontal in; σ_{SB} is the Stefan-Boltzmann constant; T_a [K] is the temperature of ambient (air temperature around the PV module); η_{Tref} [%] is the efficiency of converting solar energy into electrical energy of the PV module at the temperature T_{ref} and the G = 1000 W/m^2; β_{ref} [1/K] is the thermal coefficient of the PV module, and T_{ref} [K] is the reference temperature at which the efficiency of the PV module is η_{Tref}.

To determine the temperature of the PV module from eq. (10), the Euler method was used. The solution of this equation is given by the following expression:

$$T_{PV}(t+1) = T_{PV}(t) + step \cdot \mathrm{d}T_{PV}/\mathrm{d}t, \quad (19)$$

where

$$\mathrm{d}T_{PV}/\mathrm{d}t = \Big(h_w T_a + h_{rad,f}T_{sky} + h_{rad,b}T_{gr} + \\ +G(\tau\alpha)\left(1 - \eta_{T_{ref}}(1 + \beta_{ref}T_{ref})\right) - T_{PV}(t)(h_w + \\ +h_{rad,f} + h_{rad,b} - G(\tau\alpha)\eta_{T_{ref}}\beta_{ref})\Big)A/C_{PV}. \quad (20)$$

In eq. (19), t is the time in s, and $step$ is the time interval between two adjacent data pairs. To determine the temperature T_{PV} in eq. (19), it is necessary to know the initial PV module temperature. Here, it represents the initial measured temperature T_{PV}, that is, the measured temperature T_{PV} at time t = 0.

After determining T_{PV}, the values of $h_{rad,f}$ and $h_{rad,b}$ in eqs. (13) and (14) can be re-evaluated and then used to solve for T_{PV} again. This procedure can yield a nearly accurate solution after 5 to 6 iterations. This iterative approach is applied at each step of the Euler method. After solving for T_{PV}, the values of $h_{rad,f}$, and $h_{rad,b}$ in eq. (13) and (14) can be re-estimated. Subsequently, the T_{PV} can be solved again. A nearly exact solution can usually be obtained after 5 to 6 iterations. This iterative process is applied at each step of the Euler method.

The described thermal model is highly accurate because it accounts for the effects of all relevant construction and environmental parameters on PV module temperature. To accurately estimate the temperature of the PV module using the proposed model, it is crucial to correctly determine the value of the coefficient h_w.

Sparrow et al. [27] performed experiments in wind tunnel to study the effect of plate geometry and angle of attack on convective heat transfer coefficient from flat surfaces.

Neither the effects of the angle nor the geometry were found to be significant. The authors also noted that, since wind direction varies over time and is often uncertain, an equation that depends on angle would have limited practical use.

Sparrow and Tien [28] varied the elevation angle of PV modules within the range of $0° \leq \alpha \leq 90°$ and the azimuth angle of the PV modules within the range of $0° \leq \beta \leq 45°$. The experiments found that the coefficient h_w is only slightly sensitive to changes in the angles α and β. The change in coefficient h_w due to variations in angle β over the interval $0° \leq \beta \leq 45°$ does not exceed 1%. Therefore, for practical calculations, one can presume that the convection coefficient h_w does not depend on the angle β, which is consistent with the findings published by Motwani et al. [29] and Abdel-Moneim [30]. This is because of the three-dimensional nature of the wind.

In accordance with these conclusions, the power-law form of correlation between the wind convection coefficient h_w, and the magnitude of the local wind velocity, v_w is adopted:

$$h_w = a + bv_w^c, \qquad (21)$$

which is consistent with [13] and the majority of correlations of this type (see Table 1).

The coefficients a, b, and c are unknown and they are determined so that the sum of the squared deviations between the temperature of PV module T_{PV} calculated using expression (19), where the coefficient h_w is computed using correlation (21) and the corresponding experimentally determined (measured) temperature T_{PVi} is minimized. Thus, the function that needs to be minimized is as follows:

$$F = \sum_i (T_{PV} - T_{PV_i})^2. \qquad (22)$$

To calculate the objective function (22), the computer code is developed in the MATLAB software package, where the "particleswarm" algorithm of MATLAB's Global Optimization Toolbox function is applied to minimize the objective function. The vector of control variables, whose element values are optimized, has the following form:

$$\mathbf{u} = [a, b, c]^{\mathrm{T}}. \qquad (23)$$

The lower and upper bounds of the control variables have been chosen to ensure that they encompass their optimal values. They are as follows:

$$0 \leq a, b \leq 20, \qquad 0 \leq c \leq 2. \qquad (24)$$

3. EXPERIMENTAL SETUP

Since the objective of the study is to determine the correlation for h_w under real operating conditions for PV modules of typical construction and dimensions, temperature measurements were carried out on the PV module most commonly used in practice. Temperature measurements were conducted on the BISOL BMO255 polycrystalline silicon PV module, which has a power output of 255 W and was mounted on a frame placed on the ground surface. The temperature of the PV module was measured using the Agilent 34970A data acquisition and switch unit, along with three J-type temperature sensors. Measurements were taken every 33 s. The sensors were directly attached to the rear side of the PV module at three different positions: top, middle, and bottom, using adhesive tape. The temperature of the PV module was determined by averaging the temperatures recorded at these points on the back side of the module. The modules were oriented southward and mounted at a 43° angle, corresponding to the latitude of Prelez village (southern Serbia), where the measurements were performed.

Figure 1 provides a schematic representation of the experimental setup, and Fig. 2 shows a photograph of the real setup. The PV module was tested under full-load conditions using a 400 W halogen lamp. The additional PV module visible in Fig. 2 was not utilized in this study. Table 2 contains all the technical details of the PV module employed in this research, along with the optical properties of both the front and back surfaces of the module.

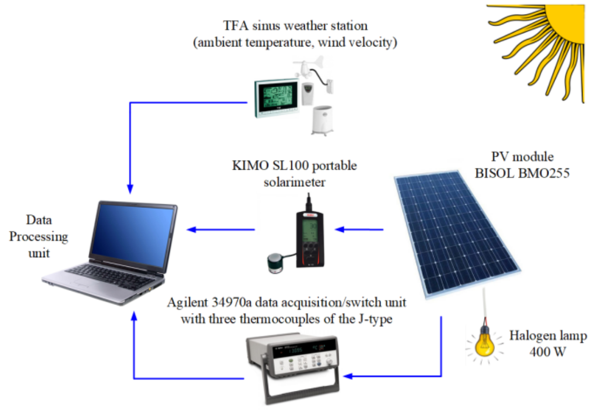

Fig. 1 – A simplified diagram of the experimental measurement equipment utilized.

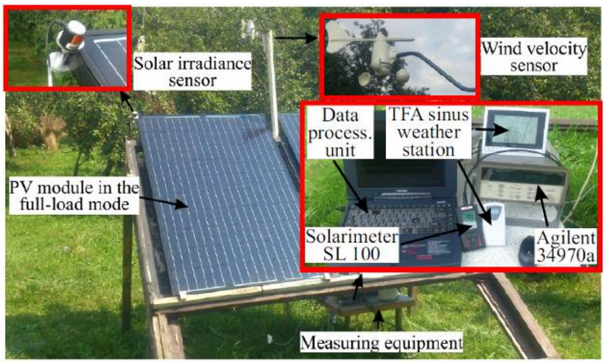

Fig. 2 – Photograph of the real experimental setup.

Table 2

Technical and optical characteristics of the considered PV module.

Characteristics of PV module [a]	BISOL BMO255
Length	1.649 m
Width	0.991 m
Nominal power	255 W
Voltage at maximum power regime / voltage at open-circuit regime	30.7 V / 38.1 V
Maximal power circuit current/short-circuit current	8.30 A / 8.90 A
Solar cell efficiency	17.5 %
Power temperature coefficient	-0.4 %/°C
Coefficient of emissivity for the front surface of PV module	0.91
Coefficient of emissivity for the back surface of PV module	0.9

[a] Characteristics at $G = 1000$ W/m^2 and $T_a = 25$ °C.

In the described thermal model for determining the temperature of PV modules, it is necessary to know not only their technical and optical characteristics but also the ambient temperature, solar irradiance, and wind velocity. These variables were measured alongside the temperature of the PV module on two different days, specifically July 11, 2018, and July 25, 2018. These dates were selected due to their differing wind speed and solar irradiance values. Solar irradiance measurements were taken using a KIMO SL100 solarimeter, while ambient temperature and wind velocity were measured with a TFA Sinus weather station (Table 3).

Table 3

Operating range of the experimental measurement equipment employed in this study.

Device		Range of operating
Agilent 34970a for J-type temperature sensors (thermocouples)		-150 °C - 1200 °C
Thermocouples (J-type)		-210 °C - 760 °C
KIMO SL100		1 W/m^2 - 1300 W/m^2, -10 °C - +50 °C
TFA weather station	Temperature of ambient	– 40 °C - + 80 °C
	Wind velocity	0 m/s - 90 m/s

4. RESULTS AND DISCUSSION

In Figure 3, the measured values of T_a, G, and v_w for the two considered days are shown. Based on these values and the optical-technical characteristics of the examined PV module, the PV module temperature was calculated every 33 s for both days using the described thermal model. The time step of 33 seconds was chosen because it corresponds to the time interval between two measurements of PV module temperature, so that the least squares deviation between the calculated temperatures and temperatures obtained by measurements pertains to the same time interval. The PSO algorithm was applied to determine the optimal values of the control variables within the range of their lower and upper bounds defined by eq. (24), at which the objective function reaches its minimum value.

The analyzed periods were intentionally selected to include strong variations in wind velocity and solar irradiance, enabling reliable validation of the transient thermal response rather than long-term performance assessment.

The PSO algorithm implemented in the MATLAB software package was tested on a personal computer with a 2.2 GHz processor and 8 GB of RAM. The population size was established at 50, while the maximum number of iterations was set to 250.

Based on the optimization results of the objective function (22) obtained using the PSO algorithm, the correlation for h_w has the following form:

$$h_w = 4.06 + 5.61 v_w^{0.735}. \tag{25}$$

The proposed correlation is valid for an open-rack-mounted PV module installed at a tilt angle of 43°, corresponding to the experimental configuration.

This correlation was obtained for wind velocities between 0 and 7.2 m/s, so it is valid within these wind velocity values. Wind velocities greater than 7.2 m/s are rare during the operation of PV modules.

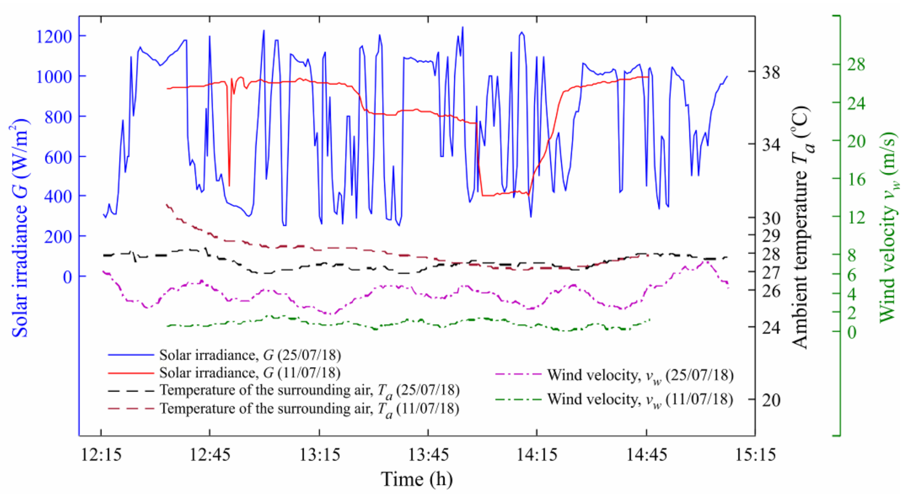

Fig. 3 – Data on G, T_a, and v_w during the two analyzed days (11/07/18 and 25/07/18).

It is interesting to note that the correlation is not linear, unlike most correlations of this type, which typically apply to wind velocities below 5 m/s. The wind velocity exponent in this correlation is 0.735, which is similar to the values in correlations (8) and (9) from Table 1 that apply to wind velocities greater than 5 m/s. This is because correlation (25) was determined for wind velocities ranging from 0 to 7.2 m/s, and higher values influenced the exponent to be less than one. Figure 4 shows a comparison of correlation (25) with similar correlations from Table 1. In the comparison, the range of wind velocities for which each correlation is valid was considered. The figure shows that correlation (25) aligns well with the other correlations of this type and is positioned between them, confirming the agreement of the present work with previous works.

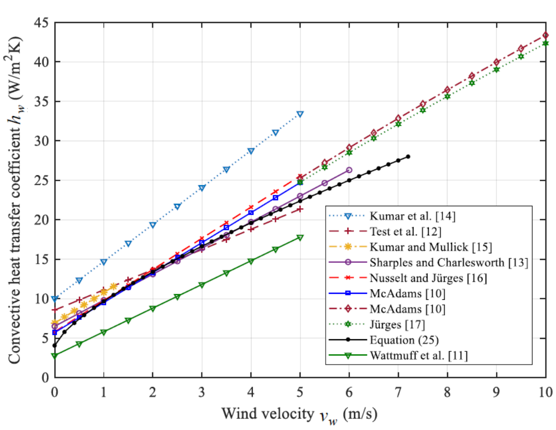

Fig. 4 – Comparison of the present study with earlier research.

At first glance, the difference between the proposed correlation (25) and the other correlations may not seem significant, but it can have a considerable impact on the estimation of the PV module temperature and, consequently, on the estimation of the power that a PV module can generate. Reference [1] notes that a temperature estimation error of just 5 °C can lead to a power estimation error of 5 W for the examined PV module, which is significant in the context of solar power plants or other systems with many PV modules.

Figure 5 compares the PV module temperature obtained from Eqs. (19) and (20), where the coefficient h_w is determined using the proposed correlation and the correlations from Table 1, based on the measured temperature of the PV module for the two specified days. Correlations (8) and (9) are not included because they apply to wind speeds above 5 m/s.

The figure clearly shows that the agreement between the calculated and measured temperature of the PV module is the best when the proposed correlation (25) is used in the thermal model, which is expected. In addition to the proposed correlation, good results are also achieved with correlations (1), (4), and (7). However, the temperature of the PV module calculated using the other correlations deviates from the measured temperature, in some cases by almost 10 °C on average. Such deviations will certainly lead to significant errors in estimating the power that a PV module can generate.

In addition to qualitative comparison, statistical accuracy indicators were evaluated. The mean bias deviation (MBD) and root mean square deviation (RMSD) between measured and calculated PV module temperatures confirm that the proposed correlation provides the best agreement among the analyzed models. The evaluation was performed using the complete measurement datasets for both analyzed days. The results are presented in Table 4.

Table 4

Estimated statistical accuracy indicators (MBD and RMSD) for PV module temperature predictions obtained using different convective heat transfer correlations.

Correlations for h_w	MBD [°C] 11/07/18	RMSD [°C] 11/07/18	MBD [°C] 25/07/18	RMSD [°C] 25/07/18
Proposed [25]	0.4	1.4	0.3	1.2
McAdams [1]	1.3	2.8	1.1	2.5
Wattmuff et al. [2]	5.1	7.1	5.0	7.0
Test et al. [3]	5.2	7.2	5.1	7.1
Sharples & Charlesworth [4]	1.3	2.4	1.0	2.2
Kumar et al. [5]	3.9	5.8	3.6	5.5
Kumar & Mullick [6]	7.2	9.2	7.1	9.1
Nusselt & Jürges [7]	1.8	3.8	1.5	3.5

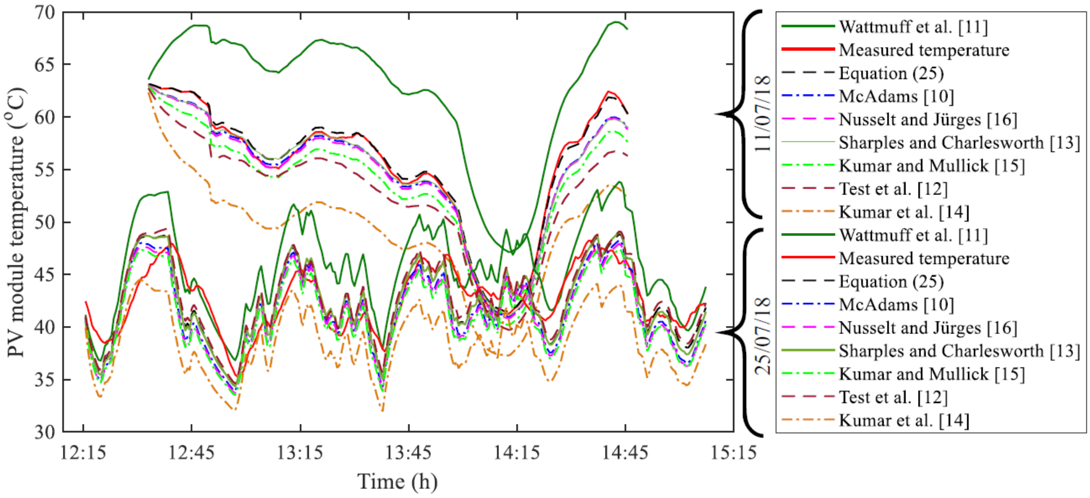

Fig. 5 – Comparison of the measured temperature of the examined PV module with the temperature calculated using Eqs. (19) and (20), where the coefficient h_w is calculated using different correlations.

5. CONCLUSIONS

The study involved measuring the temperature of a polycrystalline PV module of typical dimensions mounted on the ground, along with other meteorological parameters, under outdoor conditions. The experimental parameters were measured over two days in the village of Prelez, Zubin Potok municipality, Serbia. Based on the measured parameters, an empirical correlation was created to establish a relationship between convective heat transfer coefficient h_w and wind velocity v_w. The coefficients of the assumed power-law correlation between h_w and v_w were determined so that when substituted into the transient model for estimating the temperature of the PV module, the deviation between the estimated and measured temperature is minimized.

To estimate the PV module temperature, a transient thermal model grounded in the principle of energy conservation was applied, accounting for variations in daily solar irradiance and wind velocity throughout the measurement period. The optimization process was carried out using the PSO algorithm. The proposed correlation has the form: $h_w = 4.06 + 5.61 v_w^{0.735}$, and is valid for a range of wind velocities $0 \le v_w \le 7.2$ m/s, covering the most common wind speed values occurring during PV module operation. To validate the results, the proposed correlation was compared with similar correlations from the literature, demonstrating strong alignment between the present work and previous works. The final step involved comparing the measured PV module temperatures for two days with the values calculated by the transient thermal model, in which the coefficient h_w was determined using the proposed correlation, as well as other correlations reported in the literature. It was confirmed that the proposed correlation yields good results, while some correlations lead to a difference between the calculated and measured temperature of the PV module of nearly 10 °C on average.

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JOVAN VUKAŠINOVIĆ: Methodology.
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Writing-original draft preparation, writing-review, editing, and visualization, all authors.
All authors have read and agreed to the final version of the manuscript.

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