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PERFORMANCE OF THERMALLY BALANCED PHOTOVOLTAIC MODULE

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ABSTRACT: The intensity of heat exchange process on surface of photovoltaic module is dependent on construction and applied materials of the module. The thermal performance of a photovoltaic module was analysed based on material characteristics. We proved that nominal electric power generated by loaded photovoltaic modules operating under solar radiation decreases significantly when radiation and convection processes are disturbed due to unbalanced transfer of heat across the constituent layers of the surface. In order to comprehend the essence of matter the theoretical considerations concerning the importance of factors that disturbs the process of heat exchange was done. We noted that large values of thermal capacity and thermal resistances of surface of photovoltaic modules are responsible for inertia of heat transfer process between surface and the air. In order to eliminate the derivative process of deterioration of nominal power of photovoltaic modules caused by obstruction of heat exchange on a surface, a suggestive approach to the idea of proper thermally balanced photovoltaic modules performance was proposed. We noted that process of effective heat transfer depends strongly on low values of specific heat capacities, densities, thicknesses and surfaces of layers forming photovoltaic modules and on high values of thermal conductivities of that layers. In following paper we focused particularly on analysis of heat exchange mechanism via radiation and convection through proper thermally balanced photovoltaic module. Factors that limit the thermal performance of photovoltaic module were specified and discussed.

NOMENCLATURE

a – thermal diffusivity (m^2/s)
c_i – specific heat of constituent layer of PV module (J/kg·K)
C_M – module heat capacity (J/K)
D_I – thickness of constituent layer of pv module (m)
E – irradiance (W/m^2)
g – gravitational acceleration (m/s^2)
h – heat transfer coefficient ($W/m^2 \cdot K$)
I – electric current (A)
Nu – Nusselt number (-)
P – electric power (W)
q – heat flux (W/m^2)

P_E	–	power of solar radiation (W)
P_{el_out}	–	DC electrical power generated by loaded PV module (W)
Ra	–	Rayleigh number (-)
S	–	surface area (m^2)
S_{glass}	–	surface of external glass cover of PV module (m^2)
T	–	temperature (K)
U	–	voltage (V)
U_i	–	thermal transmittance ($W/m^2 \cdot K$)
v_w	–	wind velocity (m/s)
l	–	module length (m)

Greek symbols

λ	–	wavelength (m); thermal conductivity (W/m·K)
ν	–	kinematic viscosity (m^2/s)
β	–	thermal expansion coefficient (K^{-1}); efficiency temperature coefficient (K^{-1})
ϕ	–	panel inclination (deg)
ε_{eff}	–	emissive effective coefficient (-)
ξ	–	wind cooling factor describing the effectiveness of forced convection process (-)
ρ_i	–	density of constituent layer of PV module (kg/m^3)
σ	–	Stefan-Boltzmann constant ($W/m^2 \cdot K^4$); $\sigma = 5.7781 \cdot 10^{-8}$ $W/m^2 \cdot K^4$
η	–	conversion efficiency (%)
τ	–	transmissivity (%)
τ_α	–	the transmission-absorption factor (-)

Subscripts:

0	–	refer to T_0=298K
amb	–	ambient
cell	–	cell (module)
conv	–	convective
el	–	electric
EVA	–	Ethylene vinyl acetate
MPP	–	Maximum Power Point
PV	–	photovoltaic
rad	–	radiative
wind	–	forced convection

1. INTRODUCTION

Photovoltaic (PV) modules convert a part of solar radiation energy directly into electricity, while, the unconverted part of the solar radiation into electricity is absorbed in a PV module leading it to experience very high temperatures. A photovoltaic module has a typical efficiency of 15 to 20%. This means that the remaining 80 to 85% of the energy is in principle available in the form of heat. The PV modules are normally constructed from a number of solar cells wired in parallel and/or series and fixed on rigid non-metallic flat plate while its upper surface facing the Sun is covered with high transmittance material.

The efficiency of the photovoltaic module and its temperature are negatively correlated. It is therefore of interest to lower the temperature of the PV module by increasing the heat transfer from the PV module.

Heat transfer in the module breaks down into three transfer modes: conduction from the cells to the sides of the module, long-wave radiation between the module sides and the ground (or the roof) and the sky, convective heat transfer from the module to external air.

The aim of the work was to investigate the heat transfer intensity between the PV module and the ambient air for various solar module designs. The thermal performance of a PV module was analyzed based on material characteristics. It was proved that nominal electric power generated by loaded PV module, operating under solar radiation, decreases significantly when radiation and convection processes are disturbed due to unbalanced transfer of heat across the constituent layers of the surface.

2. HEAT TRANSFER MECHANISMS OF THE PV MODULES

The radiation arriving at the earth surface, at clean atmosphere, covers:

- ultraviolet (λ<0.4 μm), with 9% of the radiation energy,
- visible radiation (λ=0.4÷0.75 μm), with 44% of the energy,
- infrared (λ>0.75 μm), which contains 47% of the radiation energy.

Most of the infrared energy covers a broad range of wavelengths (0.75÷3.0 μm). Due to electromagnetic absorption radiation heat is produced in solids. This is easy to find out by means of indication the temperature increases between two thermodynamic states before and after irradiation in the absorbent given amount. Apart from heating, radiation entering a solar cell can separate electrons from their atomic bond, producing electron-hole pairs and due to the photovoltaic conversion a photoelectric current can flow in the circuit [1].

The discussion is based on a two-dimensional model, using the following simplifying hypotheses [9]:

- the thermal exchanges by the PV module sides are negligible (the PV module is very thin),
- all material properties are presumed to be independent of temperature,
- the part of solar radiation which is not converted into electrical energy is absorbed by the PV cells as thermal energy.

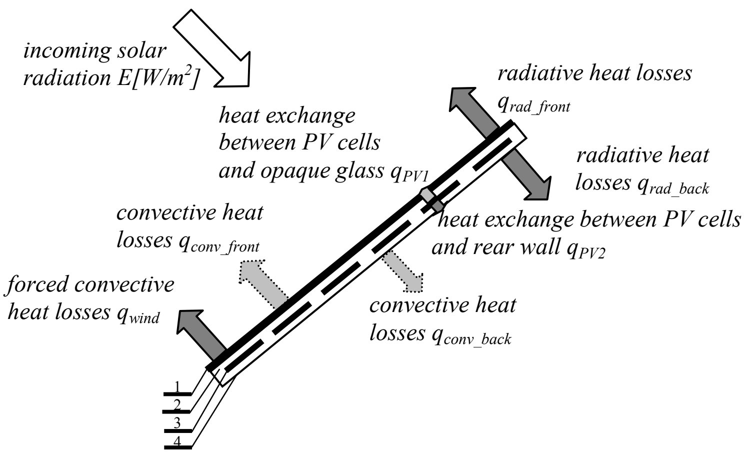

Fig. 1. Heat transfer between PV module and environment: *1* - low iron glass, *2* - EVA, *3* - PV cells, *4* - back surface (Tedlar®, glass, polyester)

Mechanism of heat exchange between the photovoltaic module and the environment includes free and/or forced convective heat transfer from the upper and rear wall of the module and radiative heat losses from the front and back surface of the module.

The intensity of heat exchange - as a result of the above mentioned mechanisms - is strongly influenced by the temperature of the front and back surfaces of the module, which are significantly dependent on: intensity of solar radiation E, absorption coefficient α of the front surface of the module, thermal conductivity of individual layers of the module (glass, EVA, silicon cells), which have a significant impact on the conductive heat transfer between PV cells and these layers.

The panel yield is defined as the amount of useful energy produced by it, whereas the panel efficiency is defined as the yield divided by solar energy received by the system.

$$\eta_{el} = \frac{P_{\max}}{E \cdot S} = \frac{I_{MPP} \cdot U_{MPP}}{E \cdot S} \quad . \tag{1}$$

Solar cells and solar panels work best at certain temperatures, according to their material properties. It is a well-known that the electrical efficiency of the crystalline silicon solar cell drops with increase in operating temperature. The electrical efficiency η_{el} is given as a function of temperature:

$$\eta_{el} = \eta_0 \left[1 - \beta\left(T_{cell} - 298K\right)\right], \tag{2}$$

with η_0 – efficiency of the module at temperature of 298 K and silicon efficiency temperature coefficient: $\beta = -4{,}5 \cdot 10^{-3}\ K^{-1}$ [2] or $\beta = -6{,}4 \cdot 10^{-3}\ K^{-1}$ [3].

The distribution of absorbed by PV module solar radiation depends on Sun altitude, azimuth, and on sky clearness, PV module slope and on the optical properties of the panel's materials. The absorption factor of a PV cell is defined as the fraction of incident solar irradiance that is absorbed by the cell. This absorption factor is one of the major parameters determining the cell temperature under operational conditions. Because solar cells are semiconductor devices, solar cells are spectrally selective absorbers, implying that in principle the absorption factor of the absorbers in a PV module is lower than the absorption factor of a black absorber in a conventional solar thermal collector. The transmission-absorption factor τ_α of the PV module can be calculated with the use of an optical model, which calculates the coefficients of each material reflection within the PV-laminate, using the Fresnel equations. The solar radiation is assumed to have no net polarisation, so the incoming light was split in 50% parallel and 50% transverse polarisation [2]. The calculation is based on the assumption of specular reflection, so the diffuse reflection is not taken into account. The fact, that PV- laminate does not present a homogenous surface, but consists of different parts (PV- cells, EVA, the spacing between cells) makes the calculations more difficult. For each part τ_α should be calculate separately and then weighted with the respective surface areas.

Now the average value of τ_α is estimated at 0.74. Than the thermal efficiency can be calculated from the transmission-absorption factor by subtracting the electrical efficiency from τ_α according to:

$$\tau_{\alpha,eff} = \tau_\alpha - \tau\eta_{el}, \tag{3}$$

where $\tau = 0.92$ is the transmissivity of the glass cover. This obtained amount of absorbed solar energy is transformed into the thermal yield.

Convective heat transfer over hot plates has been the subject of lots of experimental studies, whose review is not the main object of this work. Empirical correlations provided by thermics handbooks were obtained for experiments, in which the air flow over the plates is well known, and have to be adapted according to specific PV conditions, where the wind flow regime varies quickly.

Convective heat losses from the opaque glass and the back wall to the ambient can be calculated form the following equations:

$$q_{conv\_front} = h_{front}\left(T_{front} - T_{amb}\right), \quad (4) \qquad q_{conv\_back} = h_{back}\left(T_{front} - T_{amb}\right). \quad (5)$$

The convection heat transfer coefficient *h* is dependent on the type of media, gas or liquid, the flow properties such as velocity, viscosity and other flow and temperature dependent properties.

Introducing Nusselt number *Nu*:

$$Nu = \frac{h \cdot l}{\lambda} \tag{6}$$

the convection heat losses from the upper surface can be estimated as:

$$q_{conv\_front} = \frac{Nu \cdot \lambda}{l}\left(T_{glass} - T_{amb}\right), \tag{7}$$

where the Nusselt number Nu can be described as by Fuji, Imura [4]:

$$Nu = 0.560\left(Ra \cdot \cos\phi\right)^{0.25} \tag{8}$$

or by Churchill [5]:

$$Nu = 0.15\left(\left(Ra \cdot \sin\phi\right) / \left(1 + \left(0.322/\Pr\right)^{\frac{11}{20}}\right)^{\frac{20}{33}}\right)^{\frac{1}{3}}, \tag{9}$$

where Rayleigh and Prandtl number:

$$Ra = \frac{g\beta\Delta T}{\nu a} l^3, \ \Pr = \frac{\nu}{a}. \tag{10}$$

The heat loss to the ambient through the back of the collector q_{conv_back} is negligible because in most cases the rear of the module is covered and the difference between the temperature and the temperature of immediate surroundings is negligible.

Heat losses from the panel front surface caused by free convection q_{conv} can be replaced by heat losses by forced convection q_{wind} [8], given by Watmuff:

$$q_{wind} = \left(2.8 + 3.0 v_w\right) \cdot \left(T_{glass} - T_{amb}\right), \tag{11}$$

where wind velocity $v_w \leq 5$ m/s.

The radiation heat losses from the upper surface [6]:

$$q_{rad\_front} = \varepsilon_{ef}\sigma\left(T_{glass}^4 - T_{amb}^4\right), \tag{12}$$

where ε_{ef} - effective coefficient of emissive (*0.92÷0.94* for glass surface [7]).

The heat loss to the ambient through the back of the collector q_{rad_back} is also negligible.

Heat exchange between PV cells and opaque glass q_{PV1} and heat exchange between PV cells and rear wall q_{PV2} takes place mostly by conduction because it occurs within a material without any motion of the material as a whole.

Equations (13) and (14) describe this phenomena:

$$q_{PV1} = \frac{1}{\frac{\lambda_{glass}}{d_{glass}} + \frac{\lambda_{EVA}}{d_{EVA}}}\left(T_{glass} - T_{cell}\right), \tag{13}$$

$$q_{PV2} = \frac{1}{\frac{\lambda_{back}}{d_{back}} + \frac{\lambda_{EVA}}{d_{EVA}}} \left(T_{back} - T_{cell} \right). \tag{14}$$

As conduction is transfer of energy within and between bodies of matter, due to a temperature gradient, it will occur as long as this gradient will last. In this case solar cells in loaded photovoltaic module can be regarded as an internal heat source. This fact greatly complicates the discussion. In most cases the heat transfer between cells and the front and back layer of the module is neglected because the temperature difference between the glass, polyester and the cells can be neglected.

To determine the specific heat transfer across outer surface of photovoltaic modules we applied the modified non-stationary energy balance equation as follows:

$$C_m \frac{\partial T}{\partial t} = P_E - \left(q_{conv\_front} + q_{conv\_back} \right) - q_{wind} - \left(q_{rad\_front} + q_{rad\_back} \right) - P_{el\_out}, \tag{15}$$

Longwave radiation from front and back surfaces (q_{rad_front}, q_{rad_back}) of modules and backside convection losses (q_{conv_back}) are considered as irrelevant in comparison with free and forced convective exchange (q_{conv_front}, q_{wind}) at frontside glass cover/air interface. That is the main reason why these factors are the only significant ones responsible for excesstive heat transfer between front cover glass and air and therefore was only used to simulate the heat transfer between the illuminated surface of loaded photovoltaic module and the ambient.

Apart form mechanical quantities such as free and forced convection losses there are quantities describing heat capacity of PV module C_m and therefore its performance:

$$C_m = S_{glass} \cdot \sum_i d_i \cdot \rho_i \cdot c_i = S_{glass} \cdot \sum_i C_{m,i} \tag{16}$$

In order to calculate the dependency between significant mechanical and performance parameters an equation of (15) was transformed to the following formula:

$$\frac{\Delta T}{\Delta t} \cdot S_{glass} \cdot \sum_i d_i \cdot \rho_i \cdot C_i = \xi \cdot \left[U_{glass} \cdot S_{glass} - \left(2.8 + 3.0 v_w \right) \right] \cdot \left(T_{glass} - T_{amb} \right) \tag{17}$$

Thermal transmitance U is derived from the following formula:

$$U = \frac{\lambda}{d} \tag{18}$$

Each photovoltaic module constructed from silicon wafers is composed of few necessarry specific layers, characterized in Table 1.

Table 1. Thermal mechanical parameters for silicon crystalline photovoltaic modules (↑ - highest values, ↓ - lowest values, h) - harmful values)

Constituent layer	λ_i, W/m·K [10]	d_i, m [10]	U_i, W/m²·K	R_i, m²·K/W	ρ_i, kg/m³ [10]	c_i, J/kg·K [10]	$C_{m,i}$, J/K
Low-iron glass	1.8	0.003 ↑h)	600 ↓h)	0.00167 ↑h)	3000 ↑h)	500 ↓	2835 ↑h)
Anti-reflecting coating	32	100×10^{-9} ↓	320×10^{6} ↑	3.13×10^{-9} ↓	2400	691	0.1 ↓
PV cell	148 ↑	225×10^{-6}	0.66×10^{6}	1.52×10^{-6}	2330	677	223.6
Ethylene vinyl acetate	0.35	500×10^{-6}	700 ↓h)	0.00143 ↑h)	960 ↓	2090 ↑h)	632
Back contact	237	10×10^{-6}	23.7×10^{6}	4.22×10^{-8}	2700	900	15.3
Tedlar	0.2 ↓	0.0001 h)	2000 h)	5×10^{-4}	1200	1250	94.5

3. RESULTS

Meteorological data was carried out in Meteorological Station of Department of Chemical Apparatus and Theory of Machines of Chemical Faculty in Gdansk University of Technology. Data set consists the values of intensity of solar radiation E, ambient temperature T_{amb}, temperature of glass cover T_{glass} of photovoltaic monocrystalline silicon module (AstroPower AP-7105 of S_{glass} = 0,63 m^2) and wind speed v_w collected during 8 representative clear blue sky days in two warmest months in whole year i.e. June and July. The mean temperature growth per time interval $\Delta T/\Delta t$ for glass cover surface have the same values of 4 K/hour for these two months and have been unified for calculation purposes. Mean values of difference between T_{glass} and T_{amb} against the mean values of radiation intensity E unified for certain period of particular days are presented in Figure 2.

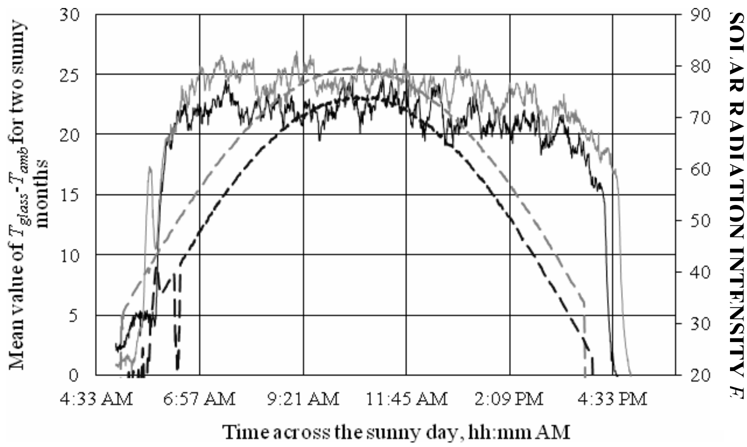

Fig. 2 Mean values of $\Delta T = T_{glass} - T_{amb}$ for June (— black solid) and July (— grey solid) versus normalised time during few sunny days against a background of the mean values of solar radiation intensity for June (···· black dashed) and July (···· grey dashed)

The mean monthly value of T_{glass} - T_{amb} for solar radiation intensity (E > 120 W/m^2) was 20.14 K and 23.73 K for June and July, respectively. The mean values of wind speed v_w measured for sunny days in June were 0.73 m/s and for July 0.38 m/s. According to equation (16) and Table 1. total heat capacity of PV module without aluminium frame is 3800 J/K and almost 75% of that value comes from front glass coating. Reference value of wind cooling factor describing the effectiveness of forced convection process ξ determined on the basis of (15) is 32. According to equation (17) we calculated the coefficient of ξ versus wind speed for June and July in order to check the dependency between constant left side of aforementioned equation with variable right side similar conditions. We obtained ξ = 35.8 for June and ξ = 41.3 for July. The result is an evidence that front glass layer/air interface heat exchange is disturbed in low wind speed conditions. High temperature difference may not be restriction provided that proper wind speed improve the performance by effective removal of heat.

4. CONCLUSIONS

Amongst all constituent layers of PV modules both the largest value of heat capacity and the lowest value of heat transmittance of front glass cover is responsible for considerable inertia of heat transfer process between glass surface and the air. It is due to significant thermal resistance of that layer. Forced convection process is an indispensable factor for effective heat transfer from the glass cover of PV module to the air and increases proportional to the wind speed. Crucial obstacle for effective heat transfer from outer surface of module is the thickness and density of that layer. External protective low-iron glass coating is characterized by the lowest value of specific heat capacity but simultaneously it is the thickest and most dense layer across the photovoltaic module which intensify the harmful impact of large heat capacity effect on successful heat exchange on front side of the module. Another important factor that limits the thermal performance of photovoltaic modules are low thermal transmittances and high thermal resistances of back layers such as ethylene vinyl acetate which hampers the heat exchange on back side of the modules.

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LEISTUNG DES THERMISCH BILANZIERTEN PHOTOVOLTAIK-MODULS

ZUSAMMENFASSUNG: Die Intensität des Wärmeaustausch-Prozesses an der Oberfläche eines Solarmoduls hängt von der Konstruktion und den verwendeten Materialien ab. Die thermischen Eigenschaften des Photovoltaik-Moduls wurden auf Grundlage der Materialeigenschaften analysiert. Wir haben gezeigt, dass die durch das belastete und unter Sonneneinstrahlung stehende Solarmodul generierte elektrische Leistung signifikant abfällt, wenn der Prozeß des Wärmeaustausches über Konvektion und Strahlung erschwert ist. Um das Wesen der Materie zu verstehen, haben wir theoretische Überlegungen zur Bedeutung der einzelnen den Wärmeaustauschprozeß störenden Faktoren durchgeführt. Wir haben festgestellt, dass hohe Werte der Wärmekapazität und des thermischen Widerstandes für die Trägheit des Wärmeaustauschprozesses zwischen der Oberfläche und der umgebenden Luft verantwortlich sind. Um den Prozeß der Nominalleistung-Minderung des Solarmoduls durch erschwerten Wärmeaustausches an dessen Oberfläche zu begrenzen, wurde das Konzept der Gewährleistung des entsprechenden Wärme-Gleichgewichts der Photovoltaik-Module vorgestellt. Wir haben festgestellt, dass der Wärmeaustausch stark von der Wärmeleitfähigkeit, der Dichte, der Dicke und der Oberfläche der einzelnen Schichten der Solarmodule abhängt. Der folgende Artikel konzentriert sich vor allem auf die Analyse des Wärmeaustausches über Strahlung und Konvektion durch die entsprechende Wärmebilanz des Solarmoduls. Es wurden Faktoren und thermische Parameter des Photovoltaik-Moduls besprochen, die den Wärmeaustausch mit der Umgebung einschränken.