EuroSun 2026

DETERMINATION OF THE CONVECTIVE HEAT TRANSFER COEFFICIENT ON PV COLLECTORS: IS THERE A NEED FOR A NEW CORRELATION?

Summary

The classical heat transfer correlations found in standard textbooks propose estimating the Nusselt number as a function of dimensionless parameters (Re, Pr, Ra). These correlations for laminar, turbulent, or mixed flows were obtained through similarity solutions and experimental measurements. However, in the literature devoted to the convective losses of PV collectors, we find correlations constructed according to the original and acknowledged McAdams model ($h=a+bxV$) where V is the average wind speed and a, and b are constants. This paper compares different correlations, investigates the sensitivity of the variation of the transfer coefficient, and proposes an experimentally validated new heat transfer correlation that is both as simple as those that depend on speed only, but which takes into account V, L, and a genuine turbulence index TI. And the result directly pertains to sustainable and solar energy transition.

Keywords: Convective heat transfer coefficient determination, convective cooling, photovoltaic collectors, conversion efficiency, meteorological conditions.

Field of application for the findings: Determination of convective heat losses by PV arrays.

Addressed audience: PV Practitioners.

1. Introduction

For the past decade, solar photovoltaic (hereafter PV) technologies have provided access to an energy source that is both inexpensive and easily modular, adapting to individual installations as well as solar parks of several hundred megawatts (IRENA, 2022). Solar energy potential is also abundant in places where electrification is least advanced (World Resources Institute, 2023). However, a high temperature of PV collectors induces a negative impact on their conversion efficiency (Emery et al., 1996).

Cooling PV collectors can be done in a variety of ways. Active cooling systems can be considered, for example, with a heat transfer fluid that circulates in channels in contact with the collectors. There are also passive cooling methods, which may be more relevant than active methods when the passive solution is air-based (rather than radiative or with phase-change materials, etc., Mariam et al., 2024). However, any cooling technique, active or passive, requires resources, whether in terms of equipment or energy, and therefore has an impact, whether economic, environmental, or social. It then becomes legitimate to question the usefulness and necessity of these cooling techniques, particularly according to the resources and needs of the different regions of the world. To estimate the extent and relevance of the cooling requirement, it is therefore necessary to estimate the efficiency loss of collectors when they produce *in situ*.

To investigate the natural or forced aero-thermal cooling of PV collectors necessarily implies the study of the heat transfers taking place on the surface of these devices. Heat transfer coefficients have been established empirically through experiments on flat plates, which at first glance are easily assimilated to a conventional PV collector. However, these expressions have been questioned more recently, because the complexity of the heat exchanges around the collectors would induce a modification of these coefficients, especially under real operating conditions (i.e. *in situ* and not in the laboratory). Hence, which expressions should be used to estimate the convective heat transfer coefficients, and consequently, the loss of conversion efficiency?

In this context, the main objective of the paper to be presented at Eurosun 2026 is to study surface heat transfer of large PV collectors in order to determine the climatic conditions under which it becomes really interesting to cool a photovoltaic array. The secondary objectives will be enunciated in the full paper.

In the next section, the paper will conduct a short review of the literature on the different cooling systems and on the heat exchanges between a PV collector and its environment. Particular emphasis will be placed on how to take into account the convective heat transfer coefficient of PV collectors in simulations, and on the different existing correlations. Subsequently, Section 3 studies a set of existing correlations and discusses their relative merits and weaknesses, and Section 4 proposes a new correlation based on the analysis of the thermophysical behaviors of PV systems to determine the heat transfer coefficient suitable for a set of experimental results.

2. Brief Discussion about Literature Review

The format of this abstract does not allow for any discussion of the state of the art on the determination of heat transfer coefficients in the context of surrounding climatic conditions, surface temperature effect on conversion efficiency, wind direction and speed, dust, turbulence, etc. Each potential influence could be the subject matter of review papers. However, the important thing to remember is that due to the preponderant importance of the collector's surface temperature on conversion efficiency, the correct determination of convection heat losses has generated intensive research activity, as evidenced by the 47 review papers and 191 research articles reported in Solar Energy alone in 2024, 2025, and 2026 (by 2026-03-12). The full paper will cite and list the relevant references used herein.

3. The convective heat transfer coefficient

As early as 1977, Evans and Florschuetz presented in Solar Energy a correlation between collector temperature and conversion efficiency, in the following simplified form:

$$\eta = \eta_r[1 - \beta(T_s - T_r)] \qquad \text{(eq.1)}$$

In this equation, η is the efficiency of the collector, $\eta_r$is the reference efficiency (i.e. at temperature T_r and irradiance G of 1000 W.m^{-2}), T_S is the temperature of the collector, and $\beta$is the temperature coefficient, which depends on the material and is of the order of 0.0041K^{-1} for silicon (Evans & Florschuetz, 1977). The path to derive this equation is detailed in 1981 by Evans alone. This equation is the result of a simplification that takes into account parameters averaged over a month during daylight hours, and which neglects a number of terms, such as the intensity coefficient, which correlates light intensity with collector efficiency (Evans, 1981). However, equation (1) shows that, in the case of materials with a positive β coefficient, the conversion efficiency of solar energy into electrical energy decreases with increasing temperature of the PV collector. For silicon-based collectors, this is a loss of about 0.5% efficiency per Kelvin (or Celsius). For the sake of consistency, in the remainder of the paper, the temperature of a collector T_S will be considered uniform over the surface. Hence, is it worth investing energy to cool the collectors and improve the efficiency? To answer the question, in outdoor spaces such as fields or roofs, when heat extraction is provided by convection, the transfer coefficient must be determined.

To estimate the convective heat transfer coefficient, a widely used method is to determine the main characteristics of the flow (surface geometry, flow regime, fluid properties) in order to calculate several dimensionless numbers, such as Reynolds Re and Prandtl Pr numbers. From the latter, the Nusselt number Nu is obtained, a dimensionless ratio of convection over conduction heat transfer. Correlations for Nu were obtained from experiments carried out in labs throughout the 20th century, and nowadays a plethora of classic textbooks on heat transfer, such as those of Incropera and Dewitt or Holman, propose several correlations for different geometries, flow regimes, fluids, temperature ranges, etc.

However, many works published in the literature prefer to use simpler correlations that decorrelate h from any parameter except one: the wind speed V, in the form $h = a V + b$. The most fundamental of them being that of McAdams found in his book in 1954, published in 1942, and based on 1924 data from Jürges.

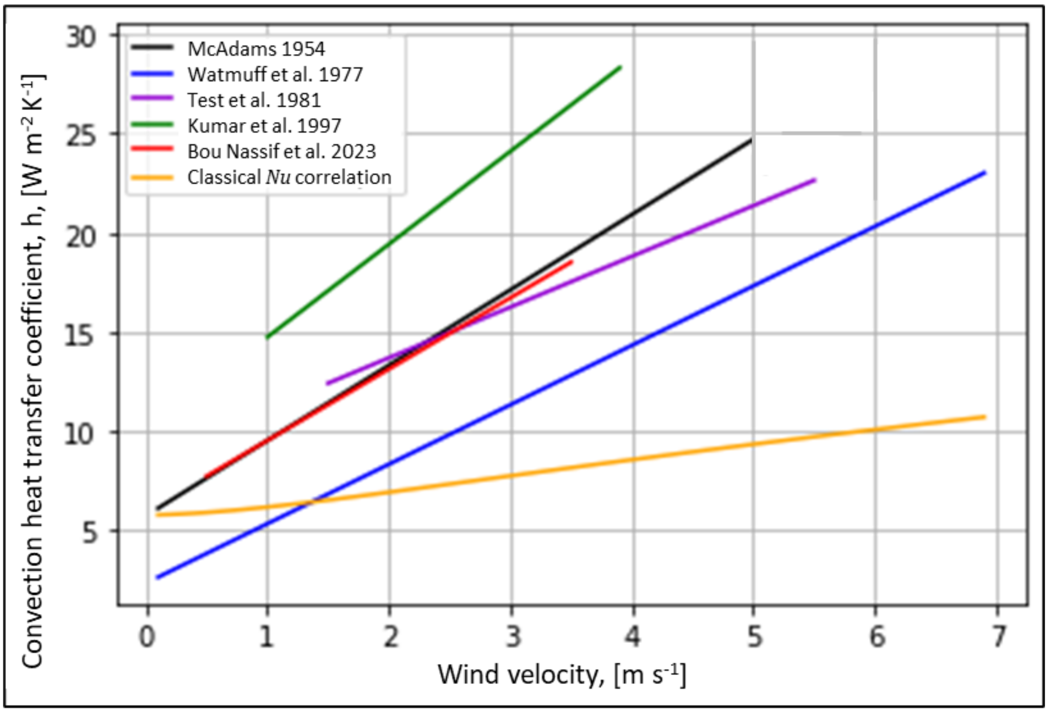

Fig. 1 Graphical representation of the variation of the convection heat transfer coefficient as a function of wind speed according to different studies.

Interestingly, the experimental results of Bou Nassif et al. (2023) on the speed range of 0.5 to 3.5 m s^{-1} are very close to those predicted by the McAdams correlation (Fig. 1). However, it must be borne in mind that while solar PV collectors can be assimilated to plates, on fixed installations, they are inclined with respect to the horizontal and therefore to the average direction of the wind which strikes them. The paper will discuss several of these correlations (by Drake, (1949); Motwani et al., (1985); Ramirez, et al., (2022); Watmuff et al., (1977); Test et al., (1981), etc…).

4. The path to a novel heat transfer correlation

Despite the physical interest of a coefficient that depends on several parameters, like the length of the panel, for instance, the "classical" Nu-based correlations (Incropera et al., 2007) can be more or less close to linear correlations and experimental results, depending on the experimental parameters and conditions considered. In addition, the different linear correlations provide very different convective heat transfer coefficients for a given wind speed. In an attempt to determine a more precise, yet simple, correlation that no longer depends solely on wind speed, it is essential to define which parameters have the most significant influence on the results. But first, the assumptions formulated by Faiman, (2008) to predict the temperature of a PV module using a few simple parameters – and accounting for a global rather than convective heat transfer coefficient – were revisited (not presented in this abstract). Then, to perform a sensitivity analysis of the parameters, the values of a set of experimental conditions were obtained for each of the above-mentioned linear correlations. The experimental conditions of interest are: 1) the wind speed, V; 2) the characteristic length, L, over which the wind flows; 3) the surface temperature of the PV collector, T_s , the air temperature, T_∞, and the temperature difference, ΔT, between the surface and the ambient air; 4) and a turbulence index (denoted TI and detailed in the full paper). Since each of the linear correlations is of the form $a\ V$+b, the parameters a and b were also recorded.

With the help of the experimental data, six graphs were plotted. Each graph describes one of the six parameters under consideration ($V, L, T_s, T_\infty, \Delta T,\ TI$). The values of a and b are plotted for each correlation as a function of the chosen parameter, except for the wind speed, where h is plotted directly. A linear regression is then performed on each of the scatter plots representing a, b, or h. From the coefficients of direction and determination of the lines obtained, the influence of each parameter is analyzed.

5. Results, in brief

Following the analyses, three parameters were determined to have a significant influence on the convective heat transfer coefficient. First, the most impactful parameter is, without surprise, the wind speed. Indeed, h can more than triple when going from a light wind (0.5 m/s) to an average wind (6 m/s). Secondly, two parameters seem to have a comparable but inverse influence. The characteristic length, L, of the collector over which the wind flows can lower h by a factor of 2, increasing from 1 to 5 m, while the turbulence index, TI, can double h by going from TI = 1 to 5 (explained in the full paper). The determination of these highly influential parameters sets the stage for a new correlation.

The final correlation proposed by this research is therefore:

$$h\,(V, L,\ IT) = \ 3{,}2 \times V\ - 1{,}0\ \times L +\ 1{,}1\ \times TI + 5{,}5 \qquad \text{(eq.2)}$$

6. Summary of the discussion and conclusion

How does this "new" correlation compare with the data used by McAdams, (1954); Watmuff et al., (1977); Test et al., (1981); Kumar et al., (1997); and Bou Nassif et al., (2023)? To conclude on this, it was mandatory to use data for each study separately. First, the correlation is quite close to McAdams, even closer to Watmuff et al., slightly above Test et al., and, not surprisingly, lower than Kumar et al. (here the graphs cannot be presented will be in the paper). As the first author worked with Bou Nassif and her colleagues at the end of her research thesis in Lyon (France), she had the opportunity to access the complete set of data from the measurements on the INSA building. And here, the match shows a 44% improvement in heat transfer coefficient prediction carried out with a classical Nu-based correlation.

In general, the new correlation proposed in this work gives better results than the most efficient classical correlation. Its use brings an improvement in the mean relative difference of 11%, and the maximum relative difference of 17%. These improvements are significant enough to support the relevance of the new correlation. In addition to its accuracy, the new correlation is also more easily applicable than the classical method Nu-based due to its simple form of linear combination, equation (2), and is better generalizable than single-parameter linear correlations.

7. References (not exhaustively reported to respect the 3 pages limit)

Bou Nassif, L., Giroux-Julien, S., Pabiou, H., 2023. Experimental Analysis of Convective Heat Transfer for Solar Panels in Outdoor Conditions. Private publication. Le Bourget du Lac, France.

Drake, R. M., 1949. Investigation of the Variation of Point Unit Heat-Transfer Coefficients for Laminar Flow Over an Inclined Flat Plate. Journal of Applied Mechanics, 16(1), 1-8.

Faiman, D., 2008. Assessing the outdoor operating temperature of photovoltaic modules. Progress in Photovoltaics: Research and Applications, 16(4), 307-315.

International Renewable Energy Agency, 2022. Solar energy. https://www.irena.org/Energy-Transition/Technology/Solar-energy

Kumar, S., Sharma, V. B., Kandpal, T. C., Mullick, S. C.,1997. Wind induced heat losses from outer cover of solar collectors. Renewable Energy, 10(4), 613-616.

McAdams, W. H., 1954. Heat Transmission, second ed. New York et London, McGraw Hill Book Company, Inc.

Test, F. L., Lessmann, R. C., Johary, A., 1981. Heat Transfer During Wind Flow over Rectangular Bodies in the Natural Environment. Journal of Heat Transfer, 103(2), 262-267.

Watmuff, J. H., Charters, W. W. S., Proctor, D., 1977. Solar and wind induced external coefficients - Solar Collectors. Revue Internationale d'Heliotechnique, 2, 56.

World Resources Institute., 2023. Energy Access Explorer. https://www.energyaccessexplorer.org/