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Original Research Article

Spatial and temporal analysis of wind effects on PV module temperature and performance

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ABSTRACT

Numerous models have been developed to predict the power output of photovoltaic (PV) systems as a function of insolation and ambient conditions. However, the effect of wind on module temperature, and hence performance, is only poorly incorporated into these models, and spatially distributed and (fast-varying) transient wind effects have not yet been studied in detail. In this paper, spatial distribution of temperature over a 156 × 156 mm PV mini-module is studied together with fine-time-scale temporal evolution. Tests were performed on a 2 × 3 mini-module mounted in a wind tunnel. Results show that the temperature differences can amount to 21 °C and more, depending on the wind speed and the location on the module. Apart from cooling caused by heat convection, a temperature increase generated by wind friction also occurs at the module's surface although it remains very low compared to the cooling caused by convection.

Introduction

It is well known that the conversion efficiency and power output of photovoltaic (PV) modules is significantly influenced by the operating temperature of the module. PV panel operating temperature depends upon many factors including solar irradiation, ambient temperature, panel composition, and mounting structure. Another, thus far much less studied factor affecting the temperature distribution of PV panels is the forced convection of heat due to wind flow over the panel.

Numerous models have been developed to predict the power output of PV systems as a function of insolation and ambient conditions (see section State-of-the-art). However, the effect of wind on module temperature is only poorly incorporated into these models, and spatially distributed and (fast-varying) transient wind effects, to our knowledge, have not yet been accounted for.

In this study, a PV mini-module was placed in a wind tunnel and illuminated by a halogen (Ha) light source. To test the effect of forced convection on aerodynamic heating and convective cooling on the module, module temperature and electric solar cell performance were measured under different aerodynamic conditions. Spatial differences in temperature over the module were also measured. The aim of the study was to gain more insight into the effects of forced convection on the patterns of uneven heating and cooling over a PV module under different wind conditions, and into their impact on transient fine time scale PV module performance.

State-of-the-art

Forced convection significantly influences the operation temperature and, thus, the power output of PV panels. Armstrong et al. [1] developed a thermal equivalent network of a PV module under varying atmospheric conditions, from which the module temperature can be calculated. Convection of heat was integrated by a wind-speed-dependent heat transfer coefficient, and heat transfer was assumed uniform over the PV panel. The same assumption has been made in the model of Jones et al. [2]. Tina et al. [3,4] model incorporates both electrical and thermal properties of PV modules to calculate the module's energy production. Their thermal model includes the convection of heat, but assumes that the heat transfer coefficient stays constant over time thereby neglecting any potential effects of wind. A validated model to predict the thermal and electrical performance of residential rooftop BIPV (Building Integrated PV) systems has been developed by

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Assoa et al. [5]. This model takes spatial effects into account. However, they assumed that most of the heat was extracted via an insulated air layer, hereby neglecting the convection of heat from the sunny side of the panels.

Heat convection from a surface has been studied using fundamental heat transfer theories, wind tunnel measurements and field measurements [6–9]. Using the well-known Nusselt equations, heat transfer relationships have been developed for the convection of heat from a horizontal plate in laminar and turbulent flows. However, these equations and other studies assume conditions of both uniform module temperature and spatially and temporally uniform convection of heat. Being obstacles in the wind flow, these conditions are not met for individual PV modules or modules installed in an array, and the models referred to above will only give a very rough estimate of the actual heat convection patterns and, therefore, the actual performance of the PV module.

A combination of forced and natural heat transfer over heated flat plates was proposed by Kudo et al. [10]. By considering both mass transport and fluid dynamics a relationship for the heat transfer coefficient as a function of location on the plate and air flow was developed. The problem of an unsteady free-convective laminar boundary-layer flow on a non-isothermal vertical flat plate was solved analytically by Abd-el-malek et al. [11].

Contrary to the previous approaches, this paper focuses on the temperature distribution within the PV module and local solar cell performance differences resulting from fine-scale spatial and temporal variations in the heat transfer coefficient due to the trapping of heat in the module's boundary layer. This knowledge can be used to improve PV performance modeling tools, especially for windy conditions.

Approach for measuring the thermal response of PV modules to wind

Materials and facilities

Tests were performed on an *i*-module composed of six industrial MWT (Metallization Wrap-Through) cells (Fig. 1) [12]. The module's fabrication method, buildup and performance has been elaborated by Govaerts et al. [13]. The module was embedded in a 3-mm thick polyethylene (PE) plate 30 cm long and 60 cm wide, which was mounted in a frame so that it could easily be installed at any desirable height in an airstream.

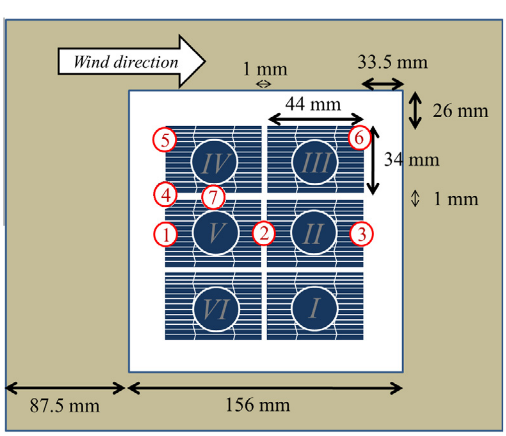

Fig. 1. Schematic overview of the *i*-module used in this study. The mini-module consisted of six industrial MTW cells (I–VI). The arrow indicates the direction of the wind and the red numbers indicate the position of the sensors for wind and module temperature measurements. The *i*-module was embedded in a PE plate (brown). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Wind tunnel experiments were conducted in the closed-return wind tunnel of the Geography Research group, KU Leuven, Belgium. This is a subsonic wind tunnel with two test sections. All experiments were conducted in the largest section, which is 7.6 m long, 1.2 m wide and 0.6 m high. For a technical diagram of the tunnel, see the study by Goossens [14].

Setup in the wind tunnel

The PV module was installed 545 cm downwind from the entrance of the wind tunnel's test section, on the central axis of the tunnel, at a height of 20.7 cm above the wind tunnel floor. The fetch in the wind tunnel was not prepared in any special way, and given these conditions, the depth of the boundary layer in the tunnel is of the order of 5–7 cm [15]. The module was thus installed in the free-stream region of the tunnel. It was installed horizontally, parallel to the wind.

Annual average wind speeds worldwide (on the continents) generally vary between 1 and approximately 6 m s^{-1} [16]. These values refer to a height of 10 m above the ground. Three free-stream wind velocities were selected during the tests: 1, 2, and 5 m s^{-1}, adequately fitting the range referred to above. Wind velocity was measured with a standard pitot tube connected to a digital Furness FC016 manometer (Furness Controls, Bexhill, UK). Wind speeds were measured with a precision of 0.01 m s^{-1}. The actual free-steam stream velocities were: 1.02 m s^{-1}, 2.01 m s^{-1}, and 5.08 m s^{-1}.

When the wind in the tunnel is turned on an internal boundary layer develops over the PE plate and the PV module. This boundary layer remained laminar over the entire length of the module as shown by the Reynolds number $Re = u_f L/v$, where u_f = free-stream velocity, L = flow length, and v = kinematic viscosity of the air. Airflow over a flat horizontal surface remains laminar as long as $Re < 5 \times 10^5$ [9]. For the wind velocities used in the tests and a flow length of 22 cm (length of the upwind PE plate + length of the PV module) Re equals 15,370 (u_f = 1 m s^{-1}), 30,288 (u_f = 2 m s^{-1}) and 76,548 (u_f = 5 m s^{-1}), which is well below the critical value of 5×10^5.

Because of the development of the boundary layer, wind speed near the module's surface will be lower than the free-stream wind speed. Therefore we also measured the wind speed close to the surface, in addition to the free-stream wind speed. With the pitot tube used the closest distance to the module at which wind speed could be measured was 2 mm. These wind measurements were performed at 7 locations over the module, as shown in Fig. 1. Because of the close proximity of the pitot tube to the surface it was necessary to correct the data for the effects caused by the pitot tube itself [17].

Temperature of the module surface was measured with K-type thermocouples (Labfacility, Sheffield, UK) glued to the surface. Temperatures were measured at the same 7 locations where the wind speeds were measured. Because all experiments were conducted in a closed wind tunnel the temperature of the air in the tunnel slightly increased during an experiment due to friction in the tunnel. To correctly detect the impact of the wind on the module's surface temperature it is necessary to correct for this effect; therefore the ambient air temperature in the wind tunnel's test section was also recorded. Two separate thermocouples were used for this purpose. Temperatures were measured in a semi-open box shielding the thermocouples from direct illumination and from direct impact of the wind so that the correct ambient temperature could be determined.

All thermocouples were calibrated prior to their installation in the wind tunnel. Their precision was 0.1 °C, and temperatures were stored every 0.25 s.