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A computational fluid dynamic study of PV cell temperatures in novel platform and standard arrangements

Ross Edgar [a,*], Steve Cochard [b], Zbigniew Stachurski [a]

[a] Research School of Engineering, College of Engineering & Computer Science Australian National University, Canberra, ACT 0200, Australia
[b] School of Civil Engineering, Faculty of Engineering & Information Technologies, University of Sydney, Sydney, NSW 2006, Australia

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ABSTRACT

Solar systems using photovoltaic (PV) modules must operate in climatic regions that range from relatively benign to hostile. The performance, lifetime and failure rate of the modules at the heart of these systems vary considerably with environmental factors and particularly temperature.

The degree to which the design of PV system platforms influences module temperatures and consequently stress outcomes is investigated. The aim is to estimate the PV-cell temperature of modules in novel platforms from the physical properties of their materials in a way that may be readily adapted to address unique conditions. The ability to analyse the thermal impact of new solar system features and elements is important to enable thermal analysis during the design phase.

A coupled computational fluid dynamic – finite element model with material properties is used to predict the PV-cell nominal temperature. It is shown that a novel PV-platform is 5 °C cooler in no wind conditions due to passive convection.

The research aim is to predict the PV-cell temperature of modules in platforms from their physical material properties in a way that may be readily adapted to consider novel conditions. The model is to estimate temperatures directly, i.e. without thermal resistance terms or test data other than for validation purposes.

In order to develop the methodology a virtual model is built of the BP350 module, whose material composition has been described by Armstrong and Hurley (2010). Analytical results are then obtained and compared with published Nominal Operating Cell Temperature (NOCT) readings from certified physical test data by BP Solar (2003) to check on the method's capabilities.

A case study of the PV module temperatures in side-by-side and novel double-layered orthogonal-offset platform (DLOOP) arrangements (Edgar et al., 2015) are studied in nominal and extreme insolation conditions. These are modelled using similar CFD methodology, including temporal and spacial discretisation scales, to that of the initial BP350 validation model.

1. Background

The economic viability of PV systems depends on their capacity to convert insolation to electricity over a lifetime and this is significantly affected by temperature factors.

The thermal resistance of PV modules has been studied previously using CFD techniques that define the temperature of the model's fluid-solid interface to match a physical test profile. The model is then used to determine the heat flux required to maintain that temperature (Jubayer et al., 2016).

The thermal resistance obtained accordingly may then be used to estimate PV cell temperatures of similar systems in other circumstances. However, the relevance of the underpinning test data to novel designs becomes uncertain when module or platform changes become significant. For novel designs, a CFD model using fundamental properties of the constituent materials is needed at least until relevant test data becomes available.

The efficiency of PV-cells, i.e. their electrical output, is known to fall as temperature rises. An efficiency fall of −0.4%/K is not unusual for PV cells generally. A more exact efficiency/temperature gradient figure is reported in commercial product data sheets because of its economic significance. Various analytic tools have been developed to assist designers quantify the impact of terrestrial environments, including wind factors and insolation levels, on PV cell temperatures (Armstrong and Hurley, 2010; García-Domingo et al., 2014; Skoplaki et al., 2008; Skoplaki and Palyvos, 2009). Using this temperature information together with the former efficiency/temperature gradient the system performance in related circumstances to those addressed may be estimated.

Less consistent is the gradual degradation rate of PV module performance with ageing and the premature loss of performance

* Corresponding author.
E-mail address: ross.edgar@physics.org (R. Edgar).

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with exposure to environmental stress factors. The US military electronic reliability prediction standard (US DoD, 1991 Table 5.8) suggests the failure rate of microcircuits generically similar to PV-cells increases 50% when the component's average junction temperature rises from 70 °C to 80 °C.

In the early 1980s field experience and failure analysis of PV modules resulted in the tightening of stress tests associated with US government procurements and backing for the PV module qualification standard IEC 61215 (Jordan and Kurtz, 2012). The Arrhenius equation is commonly used to model the relative temperature dependent acceleration of ageing rates of modules and their associated qualification test requirements (Kurtz et al., 2011; Hoffmann and Koehl, 2014). Kurtz et al. (2009) provide further advice on thermal requirements for qualification testing associated with elevated temperatures.

Jordan and Kurtz (2010) noted a strong seasonal correlation exists between degradation rate and DC energy output and accordingly describe an analytical improvement to aid PV degradation rate determinations from observation time series that include two or more years of data. They found module degradation rates are best determined from the evolution of probability density functions in place of averages (Jordan and Kurtz, 2012). What remains unclear is the degree to which the degradation observed is separately attributable to temperature, insolation or energy production as their peaks and troughs are closely correlated.

Manufacturers specifying a normal application range, which is in practise subjective, may choose conditions that are unanticipated and more benign than some customers may require. For example, Wohlgemuth et al. (2005) describe how the adhesion between the backsheet and the PV-cell potting, Ethylene-Vinyl Acetate (EVA), of one module type was qualified by damp heat tests run at 65 °C instead of 85 °C when the latter is the standard IEC 61215 and IEC 61646 PV qualification test level. These standards assume implicitly that ageing processes will be Arrhenius compliant in the test range. By contrast, the manufacturer found this was not the case with their particular product because delamination rates increased non-linearly at some temperature between 65 °C and 85 °C. The manufacturer subsequently concluded that since module use in their specified conditions should not exceed 65 °C, then the higher temperatures associated with non-linear delamination rates should not be used to accelerate module nominal ageing processes either. Product procurements for temperature environments at the top end of the general range are therefore required to pay particular attention to non-standard levels of qualification details.

Abenante et al. (2005) found from a comparison of 22 and 30 year studies involving series-parallel PV arrays near Rome that module performance-degradation was 0.05%/year and remained practically constant. This included power degradation, life-limiting wear out and external to module core component failures. By contrast, they found the module failure rate was 1.6% higher in the second survey or was increasing non-linearly at a rate of 0.06% per annum over eight years. They defined a module failure to be the premature termination of the ability of a module to provide electrical power.

Sudden failure of modules may result from cyclic thermal stress that:

- cracks an individual cell;
- fatigues an interconnect producing an open circuit;
- degrades insulation producing a short circuit;
- breaks top glass surface;
- delaminates materials due to differential expansion;
- increases the criticality of hot spots; and
- causes bypass diode failure.

BP Solar prepared a database to include all field returns of multi-Si modules since 1994 and which accounted for 0.13% of total supplies (Wohlgemuth et al., 2005), see Table 1. Higher levels of performance degradation during the first year was able to be reduced by manufacturing processes, eg. light soaking.

2. The analysis

In CFD, discrete methods are used to solve the conservation of mass, momentum and energy relationships between dependent variables of fluids; i.e. pressure, density, temperature and velocity fields. There are more variables than conservation equations and further relationships specific to the states of the fluid considered, e.g. the ideal gas law, are needed to obtain a solution. While technically sufficient, the computational effort and expense required to solve such problems involving turbulence down to applicable physical scales, i.e. where viscous effects are dissipated thermally, is generally prohibitive. Instead, various turbulence transport models have been developed to capture sub-grid scale affects, including stress-strain interactions, more or less effectively. The turbulence models draw on statistics, dimensional and conservation equation analogies that are underpinned by empirical rather than physical evidence. The effectiveness of a turbulence model is then tailored to a specific problem's requirements by the choice of model and applied refinement scale.

The analyses in this study are undertaken using commercial ANSYS CFX v.17.0 software. Diagrams of the ANSYS CFD software modules and CFX solver routines used are given in Fig. 1.

The CFX package implements a coupled solver to process the hydrodynamic equations (i.e. for ρu, ρv, ρw and p where the latter is pressure and others are momentum vectors) as a single system, i.e. set of simultaneous linear equations (ANSYS, 2016). The solver iterates on each time step trying new pressure estimates to reduce equation residuals in body centred mesh volumes and the conservation errors in the fluid domain equations for the ensemble. In the steady state analyses, a pseudo time step takes the place of the physical time step present in transient analyses to similarly move the flow variables towards low residual and high conservation targets.

The CFX-solver models the physics of thermal radiation by ray tracing between radiating surfaces on either side of transparent media, and by solving the temperature diffusion equation in solid domains using finite element methods (ANSYS, 2016).

2.1. Method

Flow charts describing the discretisation scale validation approach and case studies are presented in Figs. 2 and 3 respectively.

Fig. 2 shows a virtual model is built of a horizontal BP350 module in Nominal Terrestrial Environmental (NTE) conditions, i.e.:

Table 1
Reported PV module failure rates, representing 0.13% of total supplies (Wohlgemuth et al., 2005).

Failure description	Percent
Corrosion	45.3
Cell or interconnect break	40.7
Output lead problem	3.9
Junction box problem	3.6
Delamination	3.4
Overheating wires, diodes, terminal strip	1.5
Mechanical damage	1.4
Bypass diode	0.2