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Is enhanced radiative cooling of solar cell modules worth pursuing?

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ABSTRACT

Recent suggestions that worthwhile additional cooling of 1.0–1.5 °C below what glass covers in solar cell modules already achieve, hence raised power output, will occur via enhanced thermal radiation to the sky with special nanostructures, is examined. Rigorous thermal models indicate these observations require a much lower hemispherical emittance (E_H) for the benchmarks of silica and glass covers near 0.75. If the currently accepted value for E_H of glass of 0.84 applied even $E_H = 1.0$ would provide inadequate extra cooling. An accurate angular emittance profile for glass does predict this lower E_H. Complete models include solar heating, heating by atmospheric radiation, cooling by convection and side/base losses. Unfortunately any large lift in radiative output from raised E_H at normal cell temperatures is mostly annulled by the accompanying fall in convective cooling. The link of E_H to angular IR response points the way to novel coating approaches which may achieve the desired cooling gains. This has wider implications for buildings and other solar technologies. Direct power gains from accompanying antireflectance add value.

1. Introduction

It is well known that each degree of cooling of a silicon solar cell can add 0.4–0.5% to its power output. Thus extra average cooling of a cell by more than 1.5 °C above what current good module practice achieves in any location might be worthwhile. Recent reports using modified radiative cooling [1–3] aroused much interest. The impression arises that worthwhile power gains by enhancing output of thermal radiation relative to that from current modules are achievable. While aspects of these studies contain intrinsically interesting science detailed quantitative analysis of each of the contributions to heat gains and cooling rates in standard Si PV cell module designs indicates that an emphasis on extra radiative cooling alone will have little benefit. We show that the weak gains in heat radiated out from raised emittance relative to glass are largely annulled at the relevant temperatures by an associated drop in convective loss. Specific examples follow for a relevant range of hemispherical emittance values. It is very important that any new approach accurately references a correct benchmark for cells in current modules. The starting point for extra cooling is not a bare doped Si wafer or bare PV cell but these under glass. Glass emits more radiant heat than a silica cover as glass has a slightly higher emittance. Since silica was the reference module cover used in [2] the cooling observed will have been larger than if glass was used. Cells in glass covered modules are already cooler by around 5 °C compared to the bare wafer system from a combination of (i) net radiative cooling off the glass (ii) convective cooling of the glass cover at average local wind speeds (iii) those thermal losses which arise at other module surfaces due mainly to conduction and convection. (iv) The net generation of heat by the silicon cell. Each of these four aspects of PV module cooling and heating, from a detailed modelling perspective are addressed in Section 2. The dependence of glass and silica spectral response at all angles of incidence (from normal to 90°) across the Planck (black body) radiation range from 2.5 μm to 35 μm plays a central role in assessing what material modifications might best achieve extra module cooling. These optical properties are also essential for an accurate estimate of heat gained from absorption of incoming atmospheric radiation.

Raising hemispherical emittance (E_H) of solar transmitting module covers to close to that of a black body, was a core purpose of the nanostructured solar transmitting surface reported in Ref [2]. Achieving this will enhance net radiation output. However the detailed thermal analysis in Sections 2 and 3 following shows that impact on average daytime module operating temperature of an E_H value approaching 1.0 remains small when a complete thermal analysis is carried out. Raising the E_H value close to that of a true black body was also not well demonstrated. This is a common issue because accurate estimates of E_H values of materials which emit well is not straightforward. We will show that it is very important to accurately include contributions to emission which emerge at very

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oblique angles to the surface, that is in the zone 75–90° to the normal. However absorption or emission data in this zone is difficult and sometimes impossible to acquire experimentally. Thus it is often implied or estimated by extrapolation. For example it is hard to measure reflectance accurately at angles of incidence above 70–80°.

More specifically we will demonstrate for glass, for silica, and in general, that even if IR reflectance is very low out to angles of incidence up to around 65°, this condition is not sufficient to ensure a very high E_H. Reflectance must also not fall away significantly at angles of incidence from 70° to 90°. Such a fall off is however highly likely if the surface is effectively seen to be smooth and hence specular by incoming IR radiation. For common smooth surfaces IR reflectance increases as incidence angle rises. This detracts from the goal of a very high emittance since *a radiative cooling rate close to that of a black body requires that emittance in all exit directions remains very high.* Both float glass and smooth silica are specular for IR radiation. In Sections 3 and 4 we model the evolution of E_H as the angular aperture about the normal opens wider. This shows for smooth glass and silica, that emission in very oblique directions has a major impact on cooling rates, making them lower than often expected. This analysis also provides a better understanding of the PV cooling observations reported in Ref [2].

Improved accuracy in defining hemispherical emittance (E_H) and the flow on from that to better discrimination between different materials and surface structures according to their ability to radiate, is important elsewhere in the energy and environmental sector. For example the influence of angular dependence of IR response on hemispherical emittance will impact on heat flow from roofing, walls and windows into buildings. Cool roofs generally require a very high hemispherical emittance. However some special exceptions are worth noting. A very special recent category of cool roofs with solar absorptance below ~4% [4,5], along with surfaces developed specifically for use in some night sky cooling systems can ultilize mid-range E_H values, of order 0.6–0.3. These emit strongly only at wavelengths where the atmosphere is transparent, while reflecting most incoming atmospheric IR radiation. Their ideal performance limit is thermal equilibrium with space. In these even more atmospheric radiation is reflected if surface reflectance rises with angle of incidence because the atmosphere radiates more strongly in directions closer to the horizontal. This is the exact opposite angular behaviour of what we will show is required of the best solar module covers which need E_H close to 1.0. Such mid-E_H, IR spectrally selective surfaces should only be contemplated if their systems spend most of their operating time below or just above ambient [10], and thus they should not be considered for PV module covers, or the majority of cool roofing.

2. Heat flow analysis

The four components of heat gain or loss that must be included in any comprehensive analysis of PV cell cooling were listed in the introduction. Net radiative cooling [item (i)] is the difference between emitted and absorbed infra-red radiation. The emitted radiation is determined by the hemispherical emittance of the cover's outer surface (E_H) and its temperature (T_{cover}). The amount of absorbed thermal radiation varies with the surface material, and the intensity of incoming IR radiation from the sky. The emittance properties of the atmosphere, and ambient temperature (T_a) determine this incoming irradiance. In summer incoming IR from the sky can reach around 350–400 $\mathrm{Wm^{-2}}$ so cannot be ignored, though solar heating still dominates overall heat gain. A common approximation is to treat the clear sky as a black body emitting at a temperature T_{sky} which is lower than ambient. More accurate treatments, as used in our modelling here and in Ref [2], utilize the full IR spectral absorptance of the cover and the incoming IR spectral density of atmospheric radiation. Both vary with incidence angle. Humidity also impacts strongly on the angular profile of the incoming IR radiation, and this variation is included explicitly and accurately in our models.

The main heat input, item (iv), is absorbed solar energy less electric power delivered to an external load. Convective cooling, item (ii), depends on local wind speed, and for operating modules it dominates total cooling rate. Any test system which suppresses convective loss and raises temperatures above normal operating temperatures is a not an ideal guide in this work as a rise in steady state temperature will enhance cooling by radiation. Item (iii), side and base losses, are the minor components of cooling but must be included in a full analysis. Their magnitude is estimated using an effective U value for the module.

The decrease in radiative cooling off smooth glass due to an increase in IR reflectance at exit angles above 50° is further compounded by the extra geometric weighting at oblique incidence angles from the larger solid angles in this zone. This high angle impact is quantified in a novel way in this study. We will also show that even a black body solar transmitter at all exit angles has only moderate output gain to offer a PV module. A high IR absorptance in this high angle of incidence zone is hard to achieve in smooth or nanostructured covers with high solar transmittance. As reported in the 1980's by Rubin's group at LBNL [4,5] there was a wide spread in the various experimental E_H values reported for glass. IR data to the highest exit angles is rarely available while good calorimetric data is limited. The rigorous calorimetric study by Schleiger [6] found that for silica $E_H = 0.73 \pm 0.3$. Our thorough analysis following predicts the glass E_H value to be 0.75, not 0.84 as commonly accepted, and for silica it predicts $E_H = 0.73$ in agreement with [6].

As a result of the uncertainties in data a modelling approach to IR absorptance from 75–90° was needed for this range [4,5]. We outline below how that approximate analysis led to higher than actual values of E_H. Accurate modelling at high angles is possible when the complex indices $n(\lambda)$, $k(\lambda)$ are well specified. The old approach led to the widely used E_H value for glass of 0.84 and a standard ratio of E_H/E_0 ~0.93 for high emittance specular materials. E_0 is normal incidence emittance as found usually by IR spectrophotometers and for glass is ~0.89 at room temperature. This E_H/E_0 ratio is useful as many laboratories can measure E_0 but not E_H. Unfortunately the approximate algorithms used in the early work appear to have under-estimated IR reflectance of glass at very high incidence angles. Our analysis is based on accurate n, k values for glass which are close to those used in the early study [4,7]. The important differences we now uncover are thus traceable to divergences in the model accuracies at high angles of incidence. Agreement is close at angles of incidence up to around 75° but despite this we will show that the E_H/E_0 ratio for glass is close to 0.8 with $E_H = 0.75$.

We add support to this finding by showing that the recently observed extra PV cooling achieved with a special nano-cover relative to that found with a silica cover [1] can only have arisen because the silica had E_H value near 0.73. We also show that if the E_H value of current PV module covers was the commonly accepted glass value 0.84 this would almost eliminate extra cooling as a viable possibility. However our accurate value of around 0.75 may still make it just viable.

This issue of underestimating the hemispherical emittance integral goes well beyond solar cell cooling to other solar technologies, and to defining building surfaces thermally in energy simulation models. It also points to a need to re-examine related standards for determining hemispherical emittance of dielectrics. We foreshadow this in a detailed more general upcoming study of hemispherical emittance and IR angular properties. Hemispherical emittance accuracy becomes more important the hotter a radiating surface gets