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Microstructural, optical and thermal characterization of synthetic clay as a passive cooling medium

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ABSTRACT

This work reports on assessing the suitability of synthetic clay as a porous medium that promotes evaporative cooling for various applications, especially temperature control of photovoltaic modules. When applied to the back of these modules and supplied with a fine mist spray of water, clay reduces the operational temperatures of photovoltaic modules by 30–40 °C, depending on weather conditions. The characterization of the microstructure (crystallinity, pore size and distribution) and composition of the clay is essential in understanding the enhancements that the clay provides for evaporation. A cooling element made from the clay was tested to quantify the evaporative portion of heat transfer, while spectroscopic profiles of two photovoltaic modules under typical operational conditions were tested for thermal footprint differences. The results indicate a good match between obtained SEMs and porosity tests in estimating average pore sizes responsible for enhancing the evaporative cooling and thus lowering thermal emittance from photovoltaic modules, improving their efficiency for given ambient conditions.

1. Introduction

The degradation in performance of photovoltaic (PV) modules that accompanies the increase in their operational temperature is a major concern in terms of their power output and efficient energy conversion. This fact has prompted researchers to investigate various methods for PV cooling [1–3] to enhance the energy harness and also power output. One interesting method of achieving this desired effect is by utilizing passive cooling, which removes heat by facilitating the evaporation of a working fluid that has a high value of latent heat of vaporization per unit mass [4,5]. The main advantage of this concept of cooling is that it requires minimum input energy compared to active cooling methods, and thus reducing parasitic load that is drained from the overall output of the PV modules. Passive cooling is promoted by the presence of a porous medium and proceeds by capillary effects, provided adequate air speeds and low relative humidity ratios are predominant [6,7]. Alami [8] has utilized evaporative cooling for passive temperature control of PV modules and reported on the enhancement of its power output by more than 19% at peak time. The passive cooling setup was a layer of synthetic clay applied to the back of a PV module, supplied with a fine mist spray water that is allowed to naturally evaporate.

The investigation of the evaporation mechanism in porous media has been the subject of many analytical studies that focused on the drying mechanism through the pores. Evaporative cooling, then, can be predicted by the same parameters and variables used to explain the cooling that ensues evaporation. Two main mathematical models are available in the reviewed literature: (1) a pore network model developed by Plourde and Prat [9], which studies the interaction of surface tension forces and thermal gradients on the phase distribution within the capillaries of a porous medium, and (2) a model studying the cooling effect as the capillarity-driven viscous flow proceeds through macroscopic liquid films during the isothermal drying of porous materials [10,11]. These two models are parameter-specific and computationally intensive, and thus there is a need for a rigorous experimental evaluation of the benefits of using a porous material (synthetic clay in the present case) that promotes evaporation through its micro- and meso-pores or capillaries [12].

Thus, the objective of the current work is to experimentally investigate the evaporative cooling effect that happens through a thin layer of synthetic clay applied to a target surface. A full characterization of the clay material is planned through helium porosimetry, microstructural examination using scanning electron microscopy and powder X-ray diffraction, cooling effects testing to quantify heat transfer-related parameters and finally spectrometry to compare two devices, one with a clay layer and the other as-received. These tests will aid in arriving at a quantitative

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conclusion on the effectiveness of using porous synthetic clay as a heat sink in passive heat removal applications. Special emphasis will be made on PV applications, where heat removal without parasitic consumption of a portion of the generated electricity is an advantage, along with the ease of application of clay and its eco-friendliness.

2. Theoretical model for evaporative cooling

The mechanisms of evaporative cooling and drying in porous media are virtually identical; the latter deals with the evaporating mass of a fluid in a network of pores [9], whereas the former takes into account the latent heat of vaporization of the same fluid mass [8] to calculate the heat removed. This cooling is based on the combined effect of natural convection (no air compressor utilized) and the evaporative component resulting from the evaporation of water with the aid of a porous synthetic clay layer. Evaporative and convective heat transfer mechanisms are both strongly dependent on prevailing atmospheric conditions, such as wind speed and relative humidity. First, to estimate the convective heat transfer component, the Reynolds number, Re, and the Prandtl number, Pr for the given operational conditions are calculated, enabling an estimation of the average Nusselt number, Nu through which the convective heat transfer coefficient, h (W/m^2) is calculated and used to find the amount of heat lost by convection through Newton's law of cooling. For instances of extremely low air velocities, natural convection heat transfer is dominant, and the following ratio between the Grashof number, Gr, and Reynolds number has to be checked to affirm the dominance of natural convection according to: $\mathrm{Gr}_L/\mathrm{Re}_L^2 \gg 1$. The Grashof number is then multiplied by the Prandtel number to get the Rayleigh number, Ra, from which h is obtained through the Nusselt number, defined as:

$$\mathrm{Nu} = 0.54\mathrm{Ra}_L^{1/4}, \quad \text{Ra range } 10^4 - 10^7 \tag{1}$$

$$\mathrm{Nu} = 0.15\mathrm{Ra}_L^{1/3}, \quad \text{Ra range } 10^7 - 10^{11} \tag{2}$$

Note that the characteristic length, L_c, in this case is calculated as the surface area of the clay plate, A_s, over its perimeter, p, or $L_c = A_s/p$.

As for estimating the heat lost by evaporation in (W), the rate of feed water evaporated, $(1-f)\Delta m_w/\Delta t$ is multiplied by the latent heat of evaporation of water according to the equation:

$$\dot{Q} = \frac{(1-f)\Delta m_w h_{fg}}{\Delta t} \tag{3}$$

where f is the dimensionless fraction of water lost due to dripping or evaporation, Δm_w is the mass of water sprayed (kg), h_{fg} is the latent heat of evaporation of water (W/m^2) and Δt is the estimated time for the clay to dry (s).

3. Experimental

3.1. Clay porosity test

An Ergotech helium expansion gas porosimeter was used to measure the porosity of the synthetic clay specimen. This instrument operation is based on the principal of gas expansion as described by Boyle's law (PV = constant). Here, a known volume of helium gas at a certain pressure is isothermally expanded into the unknown void volume. The resulting equilibrium pressure after helium gas expansion is measured and the unknown grain volume, which is central to calculating the porosity, can be determined to a great deal of accuracy [12]. The advantage of using compressed helium gas manifests in its small molecular size that can penetrate the smallest clay capillaries [13]. It also has high diffusivity due to its low atomic mass and low adsorption on the clay surface. The only disadvantage of this method for this study, however, is that it is best suited for micropores, and would underestimate the values for pore sizes larger than 300 nm (macropores) [14]. The pore size can then be estimated with relation to the applied pressure according to the Washburn [15] formula:

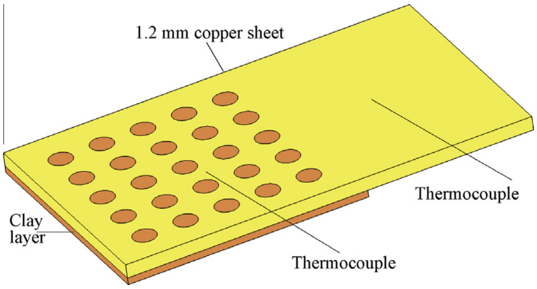

Fig. 1. Cooling element, with top clay layer removed for clarity.

$$P = \frac{-2\sigma cos\theta}{r} \tag{4}$$

where P is the absolute applied pressure, σ is the surface tension, θ is the contact angle, and r is the pore radius. For the porosity test, five cylindrical specimens were prepared from DAS-brand synthetic clay. All specimens had a 4 cm diameter, and the length was varied from 2.4 to 6.6 cm, which corresponds to the preset machine moulds. The expected pores in the specimens are macropores of open and closed varieties, and all are assumed to have a cylindrical shape [16–18].

3.2. Microstructural characterization of pores via SEM and powder X-ray diffraction

A synthetic clay specimen for microstructural examination is spread into a 2 mm layer that was fired in a drying furnace at 100 °C for 24 h. The specimen is then examined under a scanning electron microscope (SEM) to characterize the shape and size of the pores. The SEM is a VEGA3 XM by TESCAN, operating at 5 kV, where the clay samples are examined from two positions: a topological view and a cross sectional view.

For the XRD examination, a few milligrams powder sample, finely ground from remnants of the SEM examination and mounted on a silicon wafer were used. The powder X-ray diffraction (XRD) patterns provide an insight into extent of clay crystallization within the sample and a clue as to organic material incorporation by the (00l) basal spacing. The patterns are recorded in the 2θ geometry between 20 and 80° at 0.02° $2\theta\,\mathrm{s}^{-1}$ with a Bruker D8

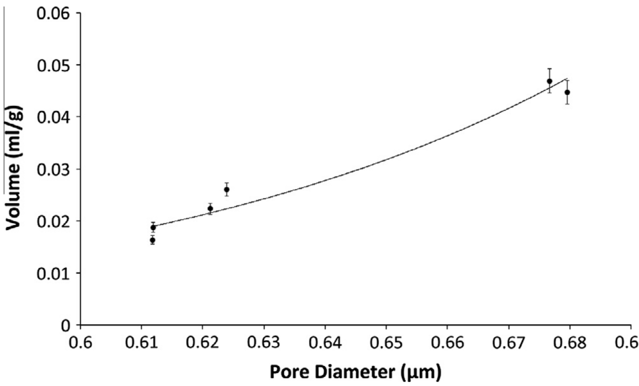

Fig. 2. Pore diameter vs. intruded volume of helium.