Simulation and Model Validation of the Surface Cooling System for Improving the Power of a Photovoltaic Module

One of the unique features of photovoltaic (PV) modules is the power drop that occurs as the silicon temperature increases due to the characteristics of the crystalline silicon used in a solar cell. To overcome this reduction in power, module surface cooling using water circulation was employed. The model performance was then conceptually evaluated and experimentally verified. A transient model was developed using energy balances and heat and mass transfer relationships from various other sources to simulate the surface cooling system. The measurements were in good agreement with the model predictions. The maximum deviation between the measured and predicted water and silicon temperature differed by less than 4°C. The maximum power enhancement in response to the cooling was 11.6% when compared with a control module. The surface cooling system also washed the module surface via water circulation, which resulted in an additional power up of the PV module in response to removal of the particles that interfere with solar radiation from the surface of the PV module. Accordingly, the cooling system could reduce maintenance costs and prevent accidents associated with cleaning. In addition, the increase in cooling water temperature can serve as a heat source. The system developed here can be applied to existing photovoltaic power generation facilities without any difficulties as well. [DOI: 10.1115/1.4004508]

Keywords: simulation, PV module, solar energy, surface cooling system, energy balance

\[ V_{oc} = \frac{AKT}{q} \ln \left( \frac{I_{sc}}{I_{e}} + 1 \right) \] (1)

Photovoltaic/thermal (PVT) technology has been employed for the cooling of PV module. The various types of PVT systems employed for the cooling of PV cells were reviewed [7], micro channel photovoltaic thermal module was developed [8]. Dubey et al. [9] found that the glass to glass type PV module was better than the glass to telledar.

To our knowledge, literatures on the transient modeling of surface cooling of PV modules are limited. Kim et al. (2007) [10] described development of a simulation model to predict the performance of a liquid film solar-assisted concentrator designed to concentrate agricultural drainage water and recover purified salts through selective crystallization. In their study, the surface temperature of the “wet” solar collectors decreased by approximately 25°C, when compared to the “dried” solar collectors, indicating that the conversion efficiency of the PV modules would be increased by about 12%. Al-Baali [6] reported that the PV module temperature was fixed at around 37°C by cooling with water, and a difference of 1.2 V above the \( V_{oc} \) of the normal panel was obtained. Moreover, Krauter et al. (2004) [5] increased the electrical yield of PV panels up to 10.3% by cooling using pumping water over the module front, even when accounting for power needed to run the pump. Cooling a PV array was also achieved without using circulating pump utilizing water flowing under its own hydraulic head [11], with the water from upstream being used to cool PV arrays and then returned downstream. The use of this system resulted in an increase in the conversion efficiency of the PV module of 12.8% [11].

In the present study, the thermal behavior of the surface cooling system was modeled for design purposes and then investigated experimentally to validate the model. One dimensional transient model was designed to predict the cooling water, PV module
silicon temperature, and evaporation rates. Experimental results obtained from the systems were compared with the model results based on geometry and climatic conditions, and power enhancement by the surface cooling of the PV module was compared with that of conventional systems.

2 Mathematical Models

A surface cooling system for simulating the water and silicon temperature is schematically shown in Fig. 2. The system consists of a pump, a storage tank, plumbing, and a distribution pipe. The system boundaries are the water, the front glass of the PV module, the silicon, and the storage tank. Each of these systems were analyzed separately, but coupled simultaneously through the heat exchange among them.

2.1 Energy Balance. The principal energy absorbed by the system during daylight hours was from direct and diffused solar radiation. The water absorbs part of this energy directly and obtains energy absorbed by the front glass of the PV module through convection. The front glass obtains energy from the silicon by conduction. Energy losses from the water occur via evaporation, convection with the air, and radiation to the ambient environment. During nighttime operation, radiative cooling of the PV module and the water can occur so that temperatures below the air temperature are possible. Energy lost by conduction from the silicon to the surroundings is ignored when insulating the back side of the PV module. The water flow along the front glass is assumed to be uniform in depth and width, and reflection of the irradiance by the front glass is assumed to be 10% [5]. The energy balance for water on the PV module is shown schematically in Fig. 3.

2.1.1 Energy Balance for the Water on the Front Glass. The energy absorbed by the water is the convection between the front glass and the water and from the solar radiation. Energy losses from the water occur via long-wave radiation exchange, convection from the water to the ambient air, and evaporation. There are two inlet and outlet energy terms for the water as well. The overall energy balance for the water on the front glass is

\[
m_w c_w \frac{dT_w}{dt} = (G_{aw} - Q_{rad,sky} + Q_{conv,wa} - Q_{conv,wa} - Q_{evap})A_t, \]

\[
+ (\dot{m}_w c_w T_w) - (\dot{m}_{out} c_w T_w) \tag{2}
\]

2.1.2 Solar Radiation Absorptance by the Water. The solar radiation absorbed by the water per unit area is

\[G_{aw} = \alpha_b G_{bt} + \alpha_d G_{dt}\]

The beam and diffuse radiation received on a PV module surface can be described as [12],

\[G_{bt} = G_b \left(\frac{\cos \theta}{\cos \theta_b}\right)\]

\[G_{dt} = G_d \frac{1 + \cos(a)}{2}\]

The absorptance of the water for beam radiation was determined using the net radiation method [13] and full details are given in Kim et al. (2007) [14].

2.1.3 Convection From the Water to the Ambient Air. Convection from the water to the air depends on the temperature difference between the water and the air and the wind speed. The convection is modeled with a linear dependence over the range of wind speeds [15].

\[Q_{conv,wa} = h_{conv,wa}(T_w - T_a)\]

\[h_{conv,wa} = (2.8 + 3.0V)\]

2.1.4 Convection From Front Glass Plate to Water. The convection between the front glass and the water is given by,

\[Q_{conv,wa} = h_{conv,wa}(T_g - T_w)\]

\[h_{conv,wa} = \frac{Nu \cdot k}{L_c}\]

Fig. 2 Schematic of surface cooling system

Fig. 3 Energy balance for the water on the PV module
From Ref. [16],

$$\text{Nu} = \left\{ 0.825 + \frac{0.387 \text{Ra}^{1/6}}{1 + (0.492/\text{Pr})^{1/6}} \right\}^2 \frac{h_{\text{conv,sg} \text{L}_{\text{c}}}}{k_{\text{a}}} \quad (10)$$

$$\text{Ra} = \frac{g \sin(a) \beta (T_a - T_s) \text{L}_{\text{c}}^3}{\nu^2} \quad (11)$$

2.1.5 Longwave Radiation Exchange Between the Water Surface and the Sky. The energy transferred by longwave radiation exchange with the lower atmosphere is given by the effective sky temperature, $T_{\text{sky}}$, is

$$T_{\text{sky}} = (T_a + 273.15) \left[ \frac{(T_d + 200)}{250} \right]^{1/4} - 273.15 \quad (12)$$

2.1.6 Energy Transferred by Evaporation. The energy transferred by evaporation between the water and the ambient air is modeled by [13]

$$Q_{\text{evap}} = 26.639 \times 10^{-3} V_0^0.5 (P_w - P_d) \frac{h_{\text{f}}}{P_f} \quad (13)$$

2.1.7 Conduction Between the Silicon and the Front Glass. The energy transferred by conduction from the silicon to the front glass depends on the temperature difference between the two solid materials. Conduction between the silicon and the front glass can be written as,

$$Q_{\text{cond,sg}} = k \frac{\left( T_s - T_{\text{sky}} \right)}{L} \quad (14)$$

2.1.8 Energy Balance for the Front Glass. The energy that enters the front glass is obtained by conduction from the silicon and is lost by convection to the water. The energy balance for the front glass is written as,

$$m_c \frac{dT_s}{dt} = (Q_{\text{cond,sg}} - Q_{\text{conv,sg}}) \Delta_c \quad (15)$$

2.1.9 Energy Balance for the Silicon. The energy balance for the silicon is made assuming the silicon can be modeled using the lumped capacity method [18]. $T_s$ is assumed to be a mean silicon temperature. The overall energy balance for the silicon is

$$m_c \frac{dT_s}{dt} = \left( (\tau x)_s G_{\text{in}} + (\tau x)_s G_{\text{in}} - Q_{\text{conv,sg}} \right) \Delta_c \quad (16)$$

The transmittance-absorptance for the beam radiation was determined using the net radiation method [11,12].

2.1.10 Energy Balance for the Water in the Storage Tank. There are one inlet and one outlet energy terms for the water in the storage tank, outlet for the outflow water from the tank and inlet for the inflow water. Evaporation from the tank is assumed to be small and is ignored because the tank is well sealed.

$$m_{\text{w}} \frac{dT_{\text{w}}}{dt} = m_{\text{load}} c_{\text{p}} (T_{\text{w}} - T_s) \quad (17)$$

3 Solution Procedures

MATLAB VERSION 7.1.0. (Mathworks, Inc., 2005) was used to solve the model equations. For the purposes of generating model predictions, ambient meteorological data were collected by a weather station (Watchdog 2800, Spectrum Technologies, Inc., Plainfield, IL). Additionally, solar radiation was measured using a LiCor LI-200SA silicon pyranometer (LI-COR, Lincoln, NE) mounted at the same angle as the PV module. Data were collected and recorded on a datalogger (GL800, Graphtec, Yokohama, Japan). The experiment was performed from May 13 to 15, 2010.

4 Experimental Methods

A prototype surface cooling system was constructed to validate the predictions of the model. The system included a PV module, pump (PW-200SMA, Wilo Pump, Korea), plumbing, and instrumentation (Fig. 4). The system was located on the roof of a three-story building at Kangwon National University, Chuncheon, Korea. A conventional PV module as a control was built next to the cooling system to compare the output power. The two PV modules were south-facing at an angle of 23 deg from horizontal. The water in the surface cooling system was poured onto the PV module and returned to the storage tank using a pump with a flow rate of 10 lpm. The water and the silicon temperature of the cooling system and the silicon temperature of the control were measured using five numbers of type T thermocouples and were recorded on a datalogger. Two thermocouples were inserted inside the PV module from the backside, touching the silicon at 100 mm from the top and bottom edge of PV module to measure the silicon temperature. Similarly, two thermocouples were placed at 100 mm from the top and bottom edge of the glass surface, respectively, to measure the water temperature on the surface of glass and the other was used to measure the water temperature in the storage tank. The output voltage and current from each module were also recorded on a datalogger to compare the power enhancement. Table 1 shows the specifications of the PV module tested in this experiment.

<table>
<thead>
<tr>
<th>Table 1 Module specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
</tr>
<tr>
<td>Open circuit voltage ($V_{oc}$)</td>
</tr>
<tr>
<td>Short circuit current ($I_{sc}$)</td>
</tr>
<tr>
<td>Optimum operating current ($I_{mp}$)</td>
</tr>
<tr>
<td>Maximum power ($P_{max}$)</td>
</tr>
<tr>
<td>Operating temperature</td>
</tr>
<tr>
<td>Cell</td>
</tr>
<tr>
<td>Dimension of module</td>
</tr>
<tr>
<td>Weight</td>
</tr>
</tbody>
</table>
5 Results and Discussion

5.1 Comparisons of the Water and Silicon Temperatures (Measured Versus Predicted). Meteorological data (solar radiation, wind speed, air temperature, and relative humidity) measured by the weather station are shown in Fig. 5. Experimental water and silicon temperatures of the cooling system were compared with predicted values simulated by the mathematical model under the same meteorological conditions and system characteristics. The predicted water temperatures from the simulation agreed well with the experimental results and deviated by no more than 3 °C at the peak evaporation and 4 °C at the lowest evaporation (Fig. 6). For the silicon temperature, the calculated results yielded good predictions relative to the experiments as well and deviated by around 4 °C at the peak and the lowest evaporations (Fig. 7). The maximum increase in cooling water temperature was 30 °C, from 5 to 35 °C, which provided an additional source of energy that can be utilized. The peak evaporation rate was 0.8 kg/m² h on the second day (Fig. 8). Additionally, the results indicated that make-up water should be added to maintain the cooling system.

5.2 Comparisons of the Power (Cooling System Versus Control). The cooling system and the control associated with the power were also compared. As shown in Fig. 9, the maximum deviation of the silicon temperature between the cooled and control module was 20 °C. Accordingly, one can predict 10% enhancement of the conversion efficiency based on the fact that the conversion efficiency of the PV module decreased by about 0.4–0.5% per each degree increase in temperature. The average voltage deviations between the cooling system and the control were 1.21, 2.24, and 1.43 V higher for each test day, with a maximum of 3.2 V being observed on the second test day (Fig. 10). Regarding the current, the difference was around 0.1 A throughout the test period (Fig. 11). Based on the voltage and current obtained from the experiment, the average power increases for each day were 3.1, 6.6, and 4.4 W, while the maximum power deviation was 7.2 W (69.3 W for the cooling system and 62.1 W for the control), which resulted in a power enhancement of 11.6% (Fig. 12). The highest power enhancement occurred on the second day due to the clear solar radiation received on the PV module (Fig. 5). During summer, the power of PV cells is lowered than during fall and spring; however, application of the cooling system developed here could lead to improve power during summer. Despite the information obtained here, further evaluation of the effects of the developed cooling system is necessary.

Fig. 5 Meteorological data collected during the experimental period

Fig. 6 Comparison of predicted and measured water temperature

Fig. 7 Comparison of predicted and measured silicon temperature

Fig. 8 Predicted evaporation rate
6 Conclusions

A surface cooling system for improving the power of a PV module using water was developed, and a simulation was performed to compare the experimental results with predicted values. The mathematical model of the cooling system yielded good predictions relative to the experiments. The deviation between the calculated and measured water temperatures was no more than 3°C at the peak evaporation, 4°C at the lowest evaporation, and around 4°C deviation was observed at the peak and the lowest evaporations for the silicon temperature. The maximum powers of the cooling system and the control were 69.3 W and 62.1 W, respectively, indicating that an improvement of 11.6% was obtained. These findings were in good agreement with the prediction of an approximately 10% improvement according to the silicon temperature difference between the cooling system and the control. Greater power enhancement could be achieved if the cooling system was operated during summer. The increase in cooling water temperature provides an additional source of energy that can be utilized. Additionally, the cooling system can achieve extra power up of PV modules by removing particles that interfere with solar radiation from the surface of cells. Finally, this system can easily be applied to the existing photovoltaic power generation facilities to improve power.

Acknowledgment

This study was partially supported by Research Institute of Agricultural Science at Kangwon National University.

Nomenclature

\[ A = \text{junction perfection factor} \]
\[ A_c = \text{area of PV module, m}^2 \]
\[ a = \text{angle from horizontal, radians} \]
\[ c_{sc} = \text{specific heat of silicon, J kg}^{-1} \text{C}^{-1} \]
\[ c_{fg} = \text{specific heat of front glass, J kg}^{-1} \text{C}^{-1} \]
\[ c_{pw} = \text{specific heat of water, J kg}^{-1} \text{C}^{-1} \]
\[ g = \text{gravitational acceleration, 9.807, m s}^{-2} \]
\[ G_{aw} = \text{rate of solar energy absorbed by water, W m}^{-2} \]
\[ G_b = \text{beam component of radiation on horizontal surface, W m}^{-2} \]
\[ G_d = \text{diffuse component of radiation on horizontal surface, W m}^{-2} \]
\[ G_{bt} = \text{beam component of radiation on tilted surface, W m}^{-2} \]
\[ G_{dt} = \text{diffuse component of radiation on tilted surface, W m}^{-2} \]
\( h_{\text{conv, wa}} \) = convection coefficient between the water and ambient air, W m\(^{-2}\)°C\(^{-1}\)
\( h_{\text{conv, gw}} \) = convection coefficient between the front glass and water, W m\(^{-2}\)°C\(^{-1}\)
\( h_g \) = heat of vaporization, J kg\(^{-1}\)
\( I_o \) = dark saturation current, A
\( I_{sc} \) = short circuit current, A
\( k \) = conduction coefficient of the front glass, W m\(^{-1}\)°K\(^{-1}\)
\( k_w \) = thermal conductivity of water, W m\(^{-1}\)°K\(^{-1}\)
\( L \) = front glass thickness, m
\( L_m \) = length of PV module, m
\( m_s \) = mass of silicon, kg
\( m_g \) = mass of the front glass, kg
\( m_{o,g} \) = mass of water on the front glass, kg
\( m_{i,g} \) = mass of water in the storage tank, kg
\( m_{out} \) = mass flow rate of water into the front glass, kg s\(^{-1}\)
\( m_{in} \) = mass flow rate of water out of the front glass, kg s\(^{-1}\)
\( N_u \) = Nusselt number
\( P_{d} \) = saturation vapor pressure at the dew point, mm Hg
\( P_T \) = atmospheric pressure, mm Hg
\( P_{sa} \) = saturation vapor pressure at water, mm Hg
\( Q_{\text{cond, gw}} \) = rate of conductive heat transfer from silicon to the front glass, W m\(^{-2}\)
\( Q_{\text{conv, gw}} \) = rate of convective heat transfer from the front glass to water, W m\(^{-2}\)
\( Q_{\text{conv, wa}} \) = rate of convective heat transfer from the glass to water, W m\(^{-2}\)
\( Q_{\text{evap}} \) = rate of evaporative heat transfer from water to the air, W m\(^{-2}\)
\( Q_{\text{rad, sky}} \) = rate of radiation heat transfer with the lower atmosphere, W m\(^{-2}\)
\( q \) = magnitude of electron charge
\( R_a \) = Rayleigh number
\( T \) = temperature, °C
\( T_a \) = air temperature, °C
\( T_{c,g} \) = cell (silicon) temperature, °C
\( T_d \) = dew point temperature, °C
\( T_{f,g} \) = front glass temperature, °C
\( T_{w} \) = water temperature in the storage tank, °C
\( T_{sky} \) = effective sky temperature, °C
\( T_{w} \) = water temperature on the front glass, °C
\( V \) = wind speed, m s\(^{-1}\)
\( V_{oc} \) = open circuit voltage, V
\( \alpha \) = thermal diffusivity of fluid, m\(^2\) s\(^{-1}\)
\( \beta \) = volumetric coefficient of expansion, K\(^{-1}\)
\( \beta \) = absorptance of the water for beam radiation
\( \gamma \) = absorptance of the water for diffuse radiation
\( \varepsilon \) = emissivity of water surface
\( \theta \) = incident angle, radians
\( \theta_z \) = zenith angle, radians
\( \nu \) = kinematic viscosity, m\(^2\) s\(^{-1}\)
\( \sigma \) = Stefan–Boltzmann constant, 5.6697 \times 10^{-8}, W m^{-2} K^{-4}
\( \tau_{b} \) = beam transmittance-absorptance product for the silicon-water system
\( \tau_{d} \) = diffuse transmittance-absorptance product for the silicon-water system

References