The Effect of Various Liquid Mediums on the Transport of Photonic Energy and its Impact on the Quantum Efficiency of Photovoltaic Cells

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Summary
Photons from sunlight with energy slightly higher than that of the band gap of silicon create electric current within a photovoltaic (PV) cell. However, many photons from sunlight have either insufficient or excess energy. This study was conducted to find the effect of different photon transmission mediums on the temperature and voltage output of photovoltaic cells. Two different photovoltaic cells were tested under a 20-watt halogen lamp with 6 transmission mediums: 5% NaCl solution, 5% sugar solution, deionized (DI) water, canola oil, extra virgin olive oil (EVOO), and the control (air). It was hypothesized that the mediums with higher specific heats would result in relatively lower temperature increases, maintain higher voltages and have increased efficiencies compared to the mediums with lower specific heats. The voltage drop for EVOO, canola oil and air were higher than that of the aqueous solutions such as 5% sugar solution, 5% NaCl, or DI water. The results show an estimated increase of 5-6% in the performance of conventional photovoltaic cells by simply placing a layer of aqueous solution above the PV cell.

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Introduction
The Sun provides the Earth with a staggering amount of energy. The hope for a "solar revolution" that one day we will all use readily available energy from the sun is an exciting promise, because on a bright, sunny day, the sun’s rays give off approximately 1,000 watts of energy per square meter of the planet’s surface, a total of 1.2 x 10^17 watts for the entire Earth (1). If we could collect all of that energy, we could easily power our homes and offices at a much lower cost. A photovoltaic cell (PV cell) or solar cell is a device that converts light (photons) into electricity. Many people recognize that solar energy is the alternative power source of the future, and the global market for photovoltaic cells and modules is forecast to surpass $134 billion by the year 2020 (2). As of now, the efficiency of PV cells has a lot of room to improve. To make solar power the clean alternative energy source of the future, we need to urgently maximize the efficiency of PV cells. Some examples of where breakthroughs in solar technology would be beneficial are rural electrification, water pumping and treatment, healthcare, communications, agriculture, and transportation (3). From electric power plants to households to commercial projects, the results of this study could be used to harness the full potential of one of the world’s leading green and sustainable power sources: solar energy.

One of the big limitations of the widespread use of PV cells is their cost-effectiveness. There are three different types of PV cells available in the market today, each with different price ranges and efficiency levels. Making monocrystalline PV cells (cells made of a single silicon crystal) is a painstaking process and expensive, but commercial-grade monocrystalline cells can have an efficiency of higher than 30%. Polycrystalline cells (cells made of many silicon crystals) are less expensive, but have an efficiency of ~15%. Amorphous cells (cells made of scraps of silicon patched together) are the cheapest, but have a low efficiency of ~10% (1, 4).

Dye-sensitized solar cells (DSSCs) use wide band gap semiconductor dyes and electrolytes to increase photon absorption. DSSCs with efficiencies of up to 10.4% have been reported for devices employing nanocrystalline TiO2 films. Natural dyes from flame tree flowers and pawpaw leaves have also been studied as sensitzers to fabricate dye-sensitized solar cells (5, 6). PV cells absorb a lot of light and heat. The voltage output of a PV cell must be dependent on some factors in addition to the type of PV cell used and the amount of sunlight it receives. A photon only needs to have slightly greater energy than that of the band gap of silicon to be absorbed, but most of the photons that come from sunlight have energies much greater than the band gap of silicon, which causes the excess energy to be turned into heat (Figure 1) (7). The efficiency of PV cells decreases as the operating temperature increases. It has been reported that an increase in temperature leads to a decrease in voltage due to the uneven expansion of the different layers of silicon (8, 9, 10). When photons are absorbed by silicon, some electrons will have acquired the energy to jump into the conduction band. The electrons in the conduction band and the holes they left behind in the valence band create an electron-hole pair. The electron motion and the movement of holes in the opposite direction produce the electric current (Figure 1b).

PV cells, used in this experiment, are essentially...
pieces of silicon with each side coated with either boron or phosphorus. The efficiency of PV cells is defined as the percentage of photons that hit the semiconductor and are converted into electricity:

$$\text{Quantum Efficiency (QE)} = \frac{\text{Current of 1 electron}}{\text{Total power of photons}}$$

This study was conducted to find the effect of liquid photon transmission mediums on the voltage output and temperature of photovoltaic cells. An objective of this study was to increase the efficiency of the PV cells using readily available and inexpensive materials such as common household items (water, sugar, salt and cooking oils). Specific heat is the amount of heat per unit mass that is required to raise the temperature by one degree Celsius (°C). It was hypothesized that liquid mediums with higher specific heats would minimize the temperature increase of the PV cells and allow them to maintain higher voltage, thus improving their performance. Six different mediums were used, including a control. Considering lower temperature and higher voltage to be indicators of higher performance, it was found that the more efficient mediums were aqueous (ionic and nonionic) rather than the organic mediums, which had lower specific heats compared to the aqueous mediums. This research shows which photon transmission mediums can be used to increase the efficiency of photovoltaic cells.

**Results**

In this study, two different photovoltaic cells (monocrystalline PV Cell I and polycrystalline PV Cell II) were tested under a 20-watt halogen lamp during 1800 seconds of exposure to a white light with six different transmission mediums (including control). All liquid mediums and their physical properties such as specific heat, density, and refractive index are listed in Table 1. To hold mediums on top of the PV cell, a boundary was made and the PV cell was connected to a Pasco Xplorer GLX™ Datalogger with Pasco voltage and temperature probes. A schematic diagram for the experimental setup is provided in Figure 2.

The effect of different mediums on the voltage of monocrystalline PV Cell I was plotted in Figure 3a. All lines in the graph represent the combined mean voltage across the two trials for 0 to 1800 seconds. It was also observed that the voltage dropped rapidly at the beginning of the experiments. The combined mean voltage of the two trials is listed in Table 2a. The combined mean voltage changes ∆ (V) were as follows: extra virgin olive oil (EVOO) (1.023V), air (0.955V), canola oil (0.950V), 5% NaCl solution (0.577V), 5% sugar solution (0.559V), and deionized (DI) water (0.506). The trend of ∆ (V) is shown in the bar graph Figure 3b.

The effect of different mediums on the temperature of monocrystalline PV Cell I was plotted in Figure 3a. All lines in the graph represent the combined mean voltage across the two trials for 0 to 1800 seconds. It was also observed that the voltage dropped rapidly at the beginning of the experiments. The combined mean voltage of the two trials is listed in Table 2a. The combined mean voltage changes ∆ (V) were as follows: extra virgin olive oil (EVOO) (1.023V), air (0.955V), canola oil (0.950V), 5% NaCl solution (0.577V), 5% sugar solution (0.559V), and deionized (DI) water (0.506). The trend of ∆ (V) is shown in the bar graph Figure 3b.

<table>
<thead>
<tr>
<th>Medium</th>
<th>Specific Heat J/g°C</th>
<th>Density g/mL</th>
<th>Refractive Index</th>
<th>Group</th>
<th>Hypothesis: ∆(T, °C), ∆(V)</th>
<th>Observation: ∆(T, °C), ∆(V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>−1.00</td>
<td>−0.001</td>
<td>−1.003</td>
<td>Group 1</td>
<td>Higher temp ∆(T)</td>
<td>Higher temp ∆(T)</td>
</tr>
<tr>
<td>Canola Oil</td>
<td>−1.09</td>
<td>−0.914</td>
<td>−1.407</td>
<td></td>
<td>Lower voltage ∆(V)</td>
<td>Lower voltage ∆(V)</td>
</tr>
<tr>
<td>EV Olive Oil</td>
<td>−1.97</td>
<td>−0.918</td>
<td>−1.465</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5% NaCl</td>
<td>−3.93</td>
<td>−1.036</td>
<td>−1.339</td>
<td>Group 2</td>
<td>Lower temp ∆(T)</td>
<td>Lower temp ∆(T)</td>
</tr>
<tr>
<td>5% Sugar</td>
<td>−4.05</td>
<td>−1.015</td>
<td>−1.342</td>
<td></td>
<td>Higher voltage ∆(V)</td>
<td>Higher voltage ∆(V)</td>
</tr>
<tr>
<td>DI Water</td>
<td>−4.19</td>
<td>−0.997</td>
<td>−1.333</td>
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</table>

Table 1. Physical properties of various liquid mediums used for this study. a = literature value of specific heat in J/g°C (at ~25°C), b = literature value of density in g/mL (at ~25°C).
PV Cell I was plotted in Figure 3c. These lines represent the combined mean temperature across the two trials for 0 to 1800 seconds. As observed with the voltage change, the temperature increase was rapid at the beginning of the experiment but over time either plateaued (for aqueous mediums) or increased with a gentle slope (organic medium). The line for the control (air) lies in between those for the aqueous and organic mediums. For PV Cell I the combined mean temperature increase Δ(+T) values were as follows: EVOO (22.274°C), canola oil (20.129°C), air (16.538°C), 5% NaCl solution (14.753°C), 5% sugar solution (14.444°C), and DI water (13.784°C) (Table 2b). The trend of Δ(+T) is plotted in Figure 3d.

Similar to PV Cell I, experiments were performed with PV Cell II. The effect of different mediums on the voltage of PV Cell II was plotted in Figure 4a. These lines in the graph represent the combined mean voltage across the two trials for PV Cell II from 0 to 1800 seconds. The combined mean voltage changes Δ(-V) for two trials with each of the mediums were as follows: EVOO (0.166V), canola oil (0.171V), DI water (11.505°C), 5% NaCl solution (10.957°C), and for 5% NaCl solution (10.240°C) in Table 3b. The trend of Δ(+T) is plotted in Figure 4d.

Table 2a. GLX Voltage trend data for PV Cell I. Start voltage and end voltage was the combined mean of (1 sec, 11 data points) of two trials. SD: standard deviation of the two trials. SEM: standard error of the mean for two trials (SD/√N; N = 2). PV cell performance = (ΔV_end - ΔV_medium) / starting voltage of PV cell with air (7.559V). b) GLX Temperature trend data for PV Cell I. Start temperature and end temperature was the combined mean value (1 sec, 3 data points) of two trials.

Table 3a. GLX Performance trend data for PV Cell II. Start performance and end performance was the combined mean of (1 sec, 11 data points) of two trials. SD: standard deviation of the two trials. SEM: standard error of the mean for two trials (SD/√N; N = 2). PV cell performance = (ΔΔ performance) / starting performance of PV cell with air (7.559V).
p-value means the observed difference would happen rarely due to random sampling.

**Discussion**

The objective of this research was to determine how the voltage output and temperature of a PV cell would be affected by letting the photons pass through various liquid mediums thereby controlling the photonic energy of light hitting the PV cell. It has been reported that when a photon hits a piece of silicon, it can be absorbed only if its energy is higher than the silicon energy band gap, generating an electron-hole pair that creates electric current, and sometimes heat (7-10).

The physical properties of the liquid mediums such as specific heat, density, refractive index, and color, as well as the purity and crystallinity of the PV cells (monocrystalline or polycrystalline), might be key factors in explaining the observed results. The typical specific heat (J/g*°C) values (at ~25°C) of the mediums were as follows: DI Water, 4.19; 5% sugar solution, 4.05; 5% NaCl solution, 3.93; EVOO, 1.97; canola oil, 1.09; air, 1.00 (Table 1).

It was hypothesized that the change in voltage and temperature trends would be dependent on the specific heat of the medium, with lower specific heat mediums producing higher temperatures and lower voltages than the mediums with higher specific heat. This is due to the hypothesis that the absorbed photonic energy will increase the temperature of the mediums (of lower specific heat) causing the PV cells to heat up. The band gap energy of semiconductors tends to decrease with the increase in temperature; this is because with the increased thermal energy the atomic vibration and the interatomic spacing increases causing the band gap energy to decrease. Based on the specific heat values (Table 1), the transmitted photonic energy that would be reaching the PV cell surface can be expected as: $E_{\text{air}} > E_{\text{canola oil}} > E_{\text{EVOO}} > E_{\text{5% NaCl solution}} > E_{\text{5% sugar solution}} > E_{\text{DI water}}$, which can cause the temperature increase $\Delta (+T)$ of the medium as $\Delta T_{\text{air}} > \Delta T_{\text{canola oil}} > \Delta T_{\text{EVOO}} > \Delta T_{\text{5% NaCl solution}} > \Delta T_{\text{5% sugar solution}} > \Delta T_{\text{DI water}}$. It can also be predicted that the voltage decrease $\Delta (-V)$ trend could be: $\Delta V_{\text{air}} > \Delta V_{\text{canola oil}} > \Delta V_{\text{EVOO}} > \Delta V_{\text{5% NaCl solution}} > \Delta V_{\text{5% sugar solution}} > \Delta V_{\text{DI water}}$ because research indicates that an increase in temperature corresponds to a decrease in voltage (8, 9, 10). Although the control (air) has the lowest specific heat compared to the other mediums studied, it might also be possible that heat dissipation from the surface of the PV cell causes some loss of heat whereas the organic mediums (EVOO, canola oil) act as a heat storage medium.

If we consider the density of the mediums, the denser...
mediums will have more mass (as the volume of the liquid mediums was kept constant, except air) and photons will have more interactions while travelling through these mediums before it reaches the PV cell. Table 1 indicates that the densities (g/mL) of EVOO (~0.918) and canola oil (~0.914) are very similar to the densities of the aqueous mediums: 5% NaCl solution (~1.036), 5% sugar solution (~1.015) and water (~0.997). Air has the lowest density (~0.001) among all mediums tested. We have conducted further supplementary experiments with a 10% and 15% NaCl solution on PV Cell I, and compared the corresponding voltage and temperature change data with that of the 5% NaCl solution, to explore the effect of density, but no significant impact was observed due to this density change. Another factor to consider is the refractive index of the mediums. The refractive index is equal to the velocity of light in empty space, divided by the velocity v of light in a substance, or $n = c/v$. Incident light at the interface of two mediums is either reflected, absorbed, or transmitted (Figure 1c). The refractive indices of organic mediums such as EVOO & canola oil (~1.467) are higher compared to those of aqueous mediums (~1.333 for water) or air (~1.003) (Table 1). Due to the higher refractive indices of EVOO/canola oil, the speed of light is slower in the organic mediums causing more photon energy absorption, which could contribute to the temperature increase of the mediums thereby transferring more heat to the PV cells. Since canola oil and EVOO retain heat, the temperature of the photovoltaic cell increases rapidly. The impacts of the color of the liquid mediums on voltage and temperature changes were not investigated in this study.

Irrespective of the medium, all the starting voltages for PV Cell I were similar to each other. Such similarity in starting voltages, no matter the medium, was also observed for PV Cell II. It can be inferred that the amounts of photonic energy going into the PV cells at the beginning of the experiment were also similar. But due to a lower specific heat capacity of EVOO and canola oil compared to aqueous mediums, the PV cells with the organic mediums experienced greater temperature increases. Although the specific heat capacity of air is the lowest, the fact that EVOO had a higher temperature increase $\Delta (+T)$ causing the largest voltage drop $\Delta (-V)$, might be attributed to their higher refractive index values compared to air. There were two distinct data groups, 1) aqueous (ionic or 5% NaCl & nonionic or 5% sugar) mediums, and 2) organic hydrocarbon (EVOO, canola oil) mediums. The organic mediums (EVOO, canola oil) generated a higher temperature than the aqueous mediums (DI water, 5% NaCl solution, 5% sugar solution).

Both PV cells showed that the voltage output was highest when the temperature was lowest (which was the starting temp ~25°C). It was observed that the temperature increase of PV Cell I was greater than the temperature increase of PV Cell II. There could be a number of possible causes. The surface area of PV Cell I was less than that of PV Cell II. PV Cell I was monocrystalline (higher purity), whereas PV Cell II was a polycrystalline (lower purity) material. Although unknown, the type of coating materials on the two PV cells could also be a contributing factor since they were obtained from different manufacturers.

At the end of the experiment, the resultant voltages using the aqueous and organic hydrocarbon mediums were compared with that of the control. Overall, the performance of the photovoltaic cells (PV Cell I and PV Cell II) was increased by 5-6% (an estimated value based on change in voltage $\Delta (-V)$ when using aqueous (ionic and nonionic) mediums compared to air (Table 2a, 2b).
lamp was positioned over the PV cell at a distance of 5 centimeters from the PV cell. Pasco voltage and temperature probes were used to connect the PV cell to the GLX Datalogger that recorded voltage changes every 1/10 second and temperature every 1/2 second. The voltage (V) and the temperature in degrees Celsius (oC) of PV Cell I were recorded for 1800 seconds. To minimize any experimental error, the above process was repeated in two trials (Trial 1 and Trial 2) and the data was recorded using Pasco DataStudio software. In order to ensure that both the trials had a similar starting temperature, the panel was allowed to cool down to room temperature before performing each trial. After the first experiment as control (air), 6 mL DI (deionized) water was added on top of PV Cell I. The boundary area on top of the PV cell that holds the liquid was 21.56 cm² (5.75 cm × 3.75 cm), and the liquid height was 0.28 cm (6 cm³ / 21.56 cm²). Similarly, 6 mL of 5% NaCl solution, 5% sugar solution, EVOO and canola oil were tested for voltage and temperature changes respectively and the corresponding data were recorded using the GLX Datalogger.

Based on the increase in temperature and decrease in voltage data of the two different photovoltaic cells used in this study, it was found that the more efficient mediums were aqueous (ionic/nonionic) and had higher specific heats and lower refractive indices than the less efficient mediums, which were organic compounds and had lower specific heats and higher refractive indices. This research shows that common household items such as salt, sugar, and water may be used to increase the efficiency of photovoltaic cells. This study was important because although solar energy may have great potential in today’s world, it cannot be fully utilized unless we optimize the power output of photovoltaic cells.

Methods

To hold the liquid mediums on top of PV Cell I (Elenco; 6 cm × 4 cm), a containment boundary was made using acrylic plastic and latex-silicone caulk and allowed to cure overnight. PV Cell I was connected to the Pasco Xplorer GLX™, model PS-2002. The 20W Ikea halogen lamp was positioned over the PV cell at a distance of 5 centimeters from the PV cell. Pasco voltage and temperature probes were used to connect the PV cell to the GLX Datalogger that recorded voltage changes every 1/10 second and temperature every 1/2 second. The voltage (V) and the temperature in degrees Celsius (°C) of PV Cell I were recorded for 1800 seconds. To minimize any experimental error, the above process was repeated in two trials (Trial 1 and Trial 2) and the data was recorded using Pasco DataStudio software. In order to ensure that both the trials had a similar starting temperature, the panel was allowed to cool down to room temperature before performing each trial. After the first experiment as control (air), 6 mL DI (deionized) water was added on top of PV Cell I. The boundary area on top of the PV cell that holds the liquid was 21.56 cm² (5.75 cm × 3.75 cm), and the liquid height was 0.28 cm (6 cm³ / 21.56 cm²). Similarly, 6 mL of 5% NaCl solution, 5% sugar solution, EVOO and canola oil were tested for voltage and temperature changes respectively and the corresponding data were recorded using the GLX Datalogger.

Following the same procedure, PV Cell II (Horizon, 5 cm × 12 cm), was also prepared with a containment boundary to hold the liquid and connected to the GLX
Datalogger on a table top. The 20-watt halogen lamp was positioned over the PV cell at a distance of 5 centimeters and Pasco voltage and temperature probes were used to connect PV Cell II to the GLX Datalogger. In order to ensure that both the trials had a similar starting temperature the panel was allowed to cool down to room temperature before performing each trial. After the first experiment as control (with no liquid medium), 16.4 mL DI water was added on top of PV Cell II. The boundary area for holding the liquid medium was 57.50 cm² (16.4 cm³ / 57.5 cm²). Accordingly, 16.4 mL of 5% NaCl solution, 5% sugar solution, EVOO and canola oil were individually tested for temperature and voltage, and the corresponding data was recorded.

The voltage and temperature outputs of the PV cells were recorded constantly throughout the 1800 second period. Two trials were performed with each medium for each of the PV cells. For each trial, a total of 18,000 data points for voltage and 3,600 data points for temperature were collected. During the experiment, ten data points for voltage were collected every second by the voltage probe. Eleven data points from the first 1 second (0-1 second) and eleven data points from the last 1 second (1799-1800 seconds) of each trial were averaged to find the mean voltage at the start and end of that trial. For every second, two data points for temperature were collected by the temperature probe. Three data points from the first 1 second and three data points from the last 1 second were averaged, respectively, to find the mean start and end temperatures of each trial.

Statistical analysis: T-tests were conducted by considering two groups of data, Group 1 (EVOO, canola oil and air) and Group 2 (5% NaCl, 5% sugar solution, and DI water) (Table 4). Results from an unpaired t-test for PV cell I voltage change Δ (-V) were as follows: Group 1 (Mean: 0.976, SD: 0.041, SEM: 0.024, N: 3) and Group 2 (Mean: 0.547, SD: 0.037, SEM: 0.021, N: 3). The two-tailed p-value was equal to 0.0002, and the confidence interval (the difference between the mean of Group 1 and Group 2) was 0.399. The 95% confidence interval of this difference was from 0.310 to 0.487. For PV Cell II, unpaired t-test results for the voltage change Δ (-V) were: Group 1 (Mean: 0.326, SD: 0.012, SEM: 0.007, N: 3) and Group 2 (Mean: 0.168, SD: 0.003, SEM: 0.002, N: 3). The two-tailed p-value was less than 0.0001, and the confidence interval (difference between the mean of Group 1 and Group 2) was 0.158. The 95% confidence interval of this difference was from 0.138 to 0.178. Similarly, t-tests were performed for temperature change Δ (+T) for both the PV Cell I (p = 0.0351) and PV Cell II (p = 0.0141), indicating that the difference between the two groups is statistically significant.

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References