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Solar Chimney Model Parameters to Enhance Cooling PV Panel Performance

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Abstract

The concept of using the Solar Chimney plays an important role in a wide range of topics to improve cooling system efficiency such as drying process, and single and multi-story buildings ventilation against temperature rising. In this paper, study the effective solar cooling chimney parameter model to enhance the performance of photovoltaic (PV) cooling system. First, a brief description of theoretical performance predictions of the solar cooling chimney also discusses the effect of the ambient wind velocity on the photovoltaic panel. Second, analysis air velocities at different points in solar cooling chimney are predicted and the temperature drop also estimated to predicted air velocities in the duct. Finally, from simulation result it was found for chimney height range 0.3 m - 3 m and at 60 ^{o}C, the air velocity increase from 0.6 to 1.78 m/s and Pressure difference between inlet and outlet increase from 0.5 to 5.3 KPa, which improve the PV panel voltage 8%.

Keywords: air cooling, natural convection, solar cell cooling, solar cooling chimney

1. Introduction

In last three decades solar chimneys (SC) are applied in different fields such as ventilation, drying process, or production of electricity systems. Solar chimney is passive elements and one of the most promising a natural power generator using the stack effect to induce buoyancy-driven airflow. Schlaich (1995) indicated solar chimney was primarily used for power generation. It utilizes solar radiation to increase the air temperature inside the SC channel and the resulting generates the buoyant flow through the channel. Photovoltaic panels have negative temperature coefficient due to which its open circuit voltage decreases by certain V/°C of rise in the panel temperature and it convert's small amount of the incident solar radiations to electricity while some amount of solar radiation is converted to heat.

Many researchers introduce many theoretical and experimental studies and focused mainly on SC structure optimization such as minimize installation cost and maximize power output. Various methods of cooling a solar cell have been previously suggested in the literature (Royne et al., 2005; Anderson et al., 2008; Kermani et al., 2009; Moshfegh & Sandberg, 1998). Most of the methods that are used for cooling of PV panel involve an active medium which requires auxiliary power. Having an active cooling system for photovoltaic cell will make it costly and complicated have the ongoing maintenance cost. Air flow due to buoyancy and heat transfer in a vertical channel heated with simulated heat source has been investigated numerically and experimentally (Akbarzadeh et al., 2009). Moshfegh and Sandberg (1998) has shown that 30% of heat flux is transfer to the unheated wall of the duct from the PV panel by radiation and then this heat is transferred to the air in the duct, this helps to increase the air temperature and in turn the air velocity. Brinkworth (2000) has presented a routine procedure to estimate the air flow under an inclined roof top PV panel and have mention the importance of radiation heat transfer in improving the air flow in the duct or the air gap between the PV panel and roof. Some work using commercial PV panels and outdoor experiments has been first carried out by (Tonui & Tripanagnostopoulos, 2008) and they focused on investigating the thermal performance of PV air collector.

This paper described the possibility of integrating the chimney effect to cool the photovoltaic cell. A mathematical model was developed and analytical performances prediction, such as the output and the power delivered by a solar chimney power plant, according to geometrical parameters, such as the height, length, cavity width and the solar radiation.

2. Description Solar Cooling Chimney (SCC)

From Figure 1, the solar radiation is incident on the transparent bottom surface of the solar chimney. These solar radiations are absorbed by the air that is under the solar chimney which eventually gets warmed up and its density decreases. The warm air will try to rise up sue to the buoyancy force and escape through the chimney. Tall chimney will provide a pressure difference between the bottom and the top which will further assist in the draft of the air. This velocity of air is utilized to drive the turbine inside the chimney that will generate the electricity.

This design consists of a dedicated absorber section in addition to the design suggested by Tonui and Tripanagnostopoulos (2008) such that it will help to enhance the natural draft of air which can be utilized for cooling of PV panels. The velocity of air rising up in the chimney is directly proportional to the energy absorbed by the air.

SCC is decided into two main parts: top part, and the middle part as shown in Figure 1.

Top part of the SCC consists of the vertical extension to the middle part. Top part will act like a chimney in this setup to enhance the natural draft created by the warm rising air.

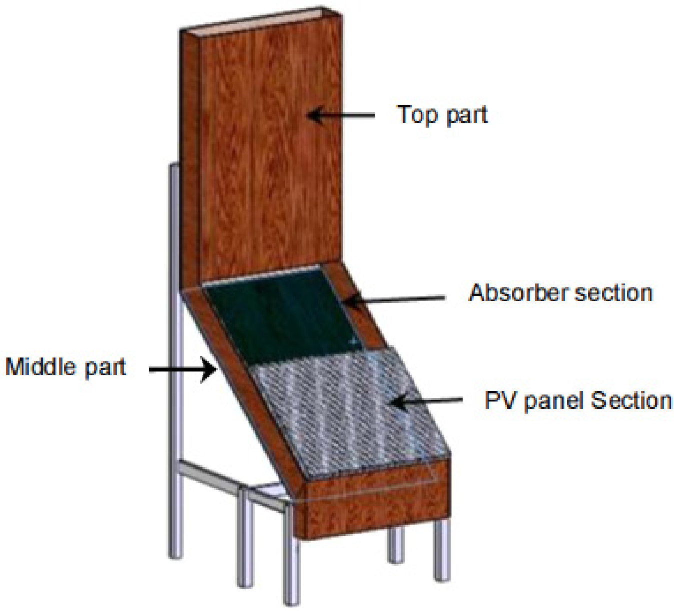

Figure 1. Solar cooling chimney

The middle part of Solar cooling chimney consists PV panel section and absorber section and designed such that its length is twice as long as the PV panel length. As shown in Figure 2 PV panel is mounted on the lower half of middle part while a transparent acrylic sheet is placed on the top half of the middle part. Middle part of solar cooling chimney is mounted at an inclination angle equal to local latitude to make sure that the PV panel and absorber section receives maximum solar radiation throughout the year.

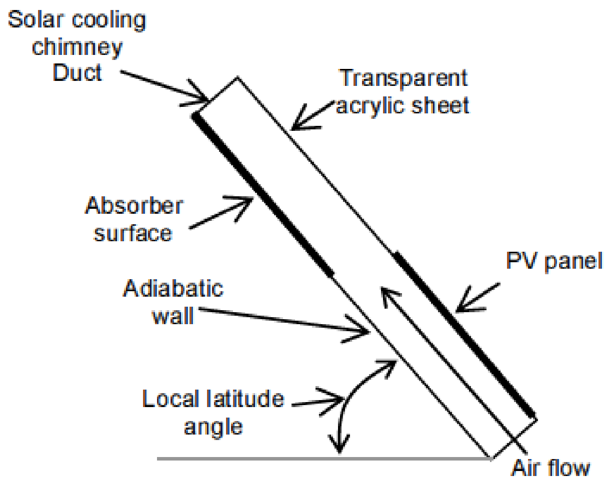

Figure 2. Middle section of solar cooling chimney

Most of the incident solar radiations will pass through the transparent acrylic sheet depending on its emissivity and reflectivity and fall on absorber surface. Absorber surface is painted black to maximize the amount of energy absorbed. As a result the temperature of the absorber surface will increase. High temperature absorber surface will transfer the heat to the air coming from the PV panel section.

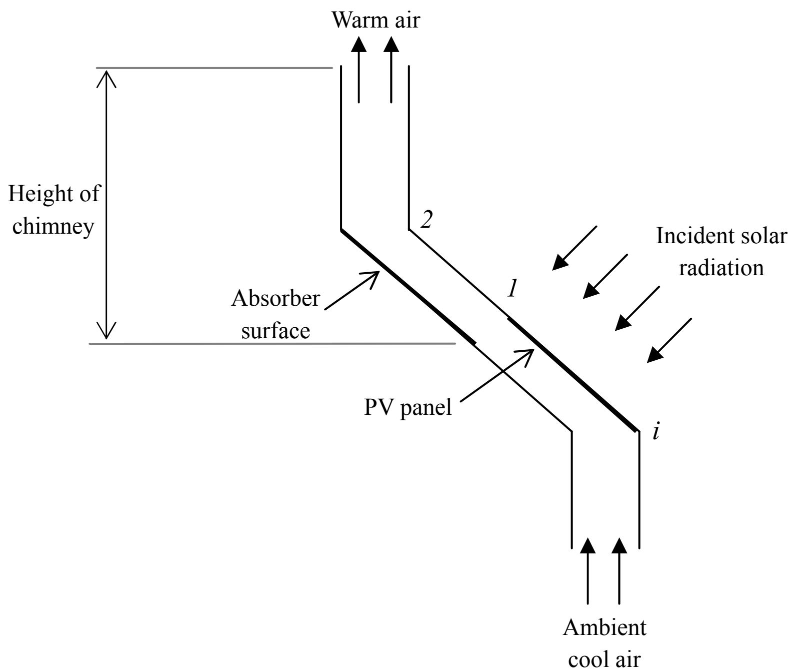

Figure 3. Solar cooling chimney dimension

Warm air with lesser density will rise upwards towards the top section. Height of the top part of SCC will assist the warm air to rise toward the top due to the static head difference. Air flow velocity will increase if we increase the height of chimney. The natural air draft in the duct induced due to the density difference between the air in the middle part and ambient air above the top part will create the suction to allow ambient air to enter from bottom of SCC as shown in Figure 3. Ambient cool air entering from the bottom of SCC will flow over the heated PV panel surface and reduce its temperature.

3. Model Theoretical Analysis

The following section presents the theoretical analysis of the solar cooling chimney as shown in Figure 4. The governing equations are derived using combination of conservation of energy and conservation of mass and momentum across the duct of the Solar Cooling Chimney to predict the values air velocities at the outlet. Energy balance equations for two separate sections in the solar cooling chimney are presented further. Figure 4 shows the PV panel section in which the PV panel is mounted on the inclined duct of the solar cooling chimney.

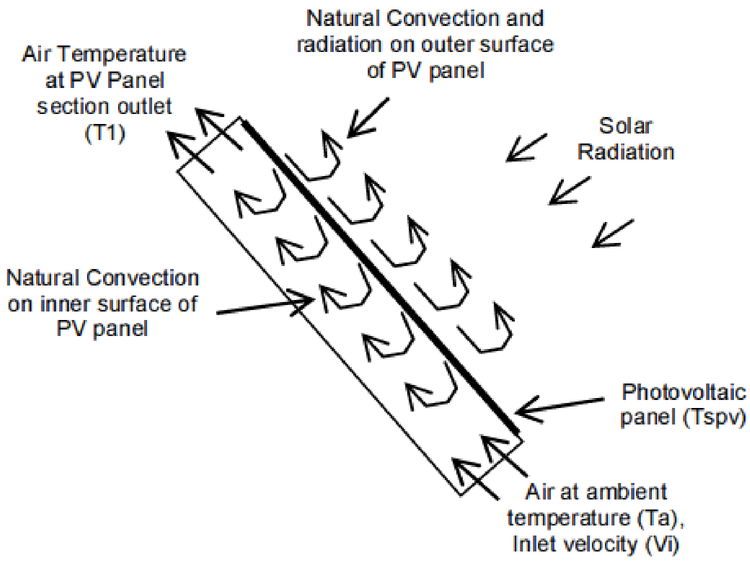

Figure 4. Heat transfer over the PV panel surface

PV panel section (point *i* to point 1)

Energy received by PV panel:

$$E_{in-pv} = I \times A_{pv} \times \left(1-\eta_{pv}\right) \times \tau_{pv} \tag{1}$$

Heat is transferred from outer and inner surface of the PV panel. Heat is transferred from outer of the PV panel via natural convection and radiation. Heat is transferred from inner surface via forced convection and radiation.

$$E_{loss-pv} = h_{nat} A_{pv} \left(T_{spv} - T_a\right) + h_{for} A_{pv} \left(T_{spv} - T_a\right) + \varepsilon\sigma A_{pv} \left(T_{spv}^4 - T_a^4\right) \tag{2}$$

Nusselt number equation for natural convection over inclined plate (Churchill & Chu, 1975):

$$Nu = \left(0.825 + \frac{0.387 Ra^{1/6}}{\left[1+(0.492/\mathrm{Pr})^{9/16}\right]^{8/27}}\right)^2 \tag{3}$$

Nusselt number equation for forced convection (Churchill and Ozoe, 1973):

$$Nu = \frac{0.3387\,\mathrm{Pr}^{1/3}\,\mathrm{Re}^{1/2}}{\left[1+\left(0.0468/\mathrm{Pr}\right)^{2/3}\right]^{1/4}} \tag{4}$$

The Reynolds number, Re is a function of the inlet velocity, V_i which is unknown.

The surface temperature T_{spv} is found by equating Equation (1) and Equation (2):

$$h_{nat} \left(T_{spv} - T_a\right) + h_{for} \left(T_{spv} - T_a\right) + \varepsilon\sigma \left(T_{spv}^4 - T_a^4\right) = I \times \left(1-\eta_{pv}\right) \times \tau_{pv} \tag{5}$$

Equation (5) is a non-linear equation.

The temperature of the air at outlet of the PV section T_1 can be determined using the log mean temperature difference between the ambient temperature and the PV surface temperature.

$$T_1 = \frac{T_{spv} - T_a}{\ln\left(\frac{T_{spv}}{T_a}\right)} \tag{6}$$

The density of moist inlet air is calculated by

$$\rho_i = \rho_{dry,i} + \rho_{v,i} \tag{7}$$

where density of dry air and water vapor are both estimated by ideal gas law.

Here, the partial pressure of water vapor can be determined by

$$P_{v,i} = \varphi_i P_{sat,i} \tag{8}$$

while the partial pressure of dry air be determined by

$$P_{dry,i} = P - P_{v,i} \tag{9}$$

where Φ_i is the relative humidity of air at inlet of PV panel, $P_{sat,i}$ is the partial pressure of vapor for saturated air at that temperature, and P is the absolute pressure.

Similar procedure is used to calculate density of air at outlet of PV panel, with

$$\frac{P_{v,i}}{P_{v,1}} = \frac{T_i}{T_1} \tag{10}$$

In the duct, pressure difference will be created by the warmer air at the inlet and cooler air at the outlet. The natural draft pressure caused by the difference in outside and inside air density is given by

$$\Delta P_s = (\rho_i - \rho_1) \times g \times H_c \tag{11}$$

where H_c is the height of chimney duct and g is the gravitational acceleration (9.81 m/s^2).

The total pressure loss in a duct can be calculated by

$$\Delta P_{lossPV} = \left(\frac{fL}{D_h} \times \frac{\rho_{avg} V_1^2}{2}\right) + \left(\frac{k \rho_{avg} V_1^2}{2}\right) \tag{12}$$

By equating Equation(11) and Equation(12), we can determined the velocity, V_1 of the air.

$$V_1 = \sqrt{\frac{(\rho_i - \rho_1) \times g \times H_c}{\frac{\rho_{avg}}{2}\left(\frac{fL}{D_h} + k\right)}} \tag{13}$$

<u>Absorber section (point 1 to point 2)</u>

Energy absorbed by absorber surface:

$$E_{in-abs} = I \times A_{abs} \times \tau_{trans} \times \tau_{abs} \tag{14}$$

Energy loss of the absorber:

$$E_{loss-abs} = h_{conv} A_{abs}\left(T_{sa} - T_1\right) + \varepsilon\sigma A_{abs}\left(T_{sa}^4 - T_1^4\right) \tag{15}$$

h_{conv} is calculated from Nusselt number for forced convection (Churchill & Ozoe, 1973).

$$Nu = \frac{0.3387\,\mathrm{Pr}^{1/3}\,\mathrm{Re}^{1/2}}{\left[1+\left(0.0468/\mathrm{Pr}\right)^{2/3}\right]^{1/4}} \tag{16}$$

Similar to the PV panel section, T_{sa} can be found by equating Equation(14) and Equation(15).

The log mean temperature of the absorber section is

$$T_2 = \frac{T_{sa} - T_1}{\ln\left(\frac{T_{sa}}{T_1}\right)} \tag{17}$$

Similar procedure is used to calculate the velocity of air, V_2 at this section.

$$V_2 = \sqrt{\frac{(\rho_1 - \rho_2)\times g \times H_c}{\frac{\rho_{avg}}{2}\left(\frac{fL}{D_h} + k\right)}} \tag{18}$$

Conservation of mass principle is used to calculate V_i. Mass balance across inlet (i) to outlet of absorber (2) is

$$\rho_2 V_2 A_{duct} = \rho_i V_i A_{duct} \tag{19}$$

$$V_i = \frac{\rho_2 V_2}{\rho_i} \tag{20}$$

The value of V_i from Equation(20) is now used in the calculation of Equation(4) in the PV section where heat transfer coefficient of forces convection can now be calculated. Iteration is continues until V_i is converged. However, since the h_c is rather small (comparative with h_n), so only one or two iteration is required (expected result).

4. Results and Discussion

In this section the theoretical solar cooling chimney model analysis as shown in Figures 5 to 7. In Figure 5, the total static pressure difference generated between the inlet and outlet of solar cooling chimney is plotted against height of chimney. It can be prominently seen that the static pressure difference across the inlet and outlet of the solar cooling chimney goes on increasing as the height of chimney increases. Temperature of outlet air has a similar effect on the static pressure of air across solar cooling chimney. This static pressure difference between the inlet and outlet of the solar cooling chimney does not behave like velocity in the Figure 7 since the major losses due to friction and minor losses due to the shape of the chimney are not includes in this static pressure.

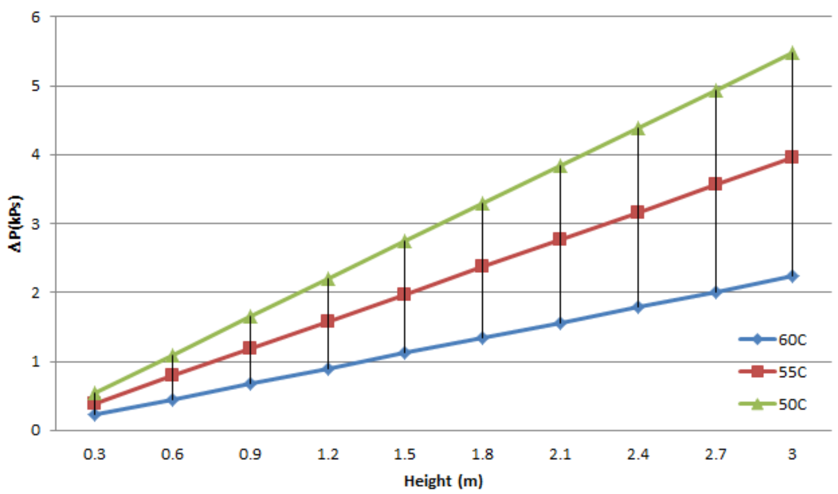

Figure 5. Static pressure difference between inlet and outlet of solar cooling chimney with respect to height

Figure 6 provides us information about the outlet air velocities that could be achieved in a chimney with its height starting from 0.1m and increasing till 1m tall. The air velocities for outlet air temperature of between 323

K (50 °C) to 333 K (60 °C) are presented. It is observed as expected that the air velocity due to natural draft will go on increasing as the solar cooling chimney height increases. Similar to the height of solar cooling chimney, temperature of outlet air will have a similar effect on the velocity if outlet air. As the temperature of outlet air will increase the velocity of air will rise. It is interesting to see that these curves have a logarithmic trend. It can be predicted that the velocity rise of air will be stagnated after certain increase of height of solar cooling chimney for different outlet air temperatures. The optimum solar cooling chimney height could be determined if this curve is extended for higher chimney heights.

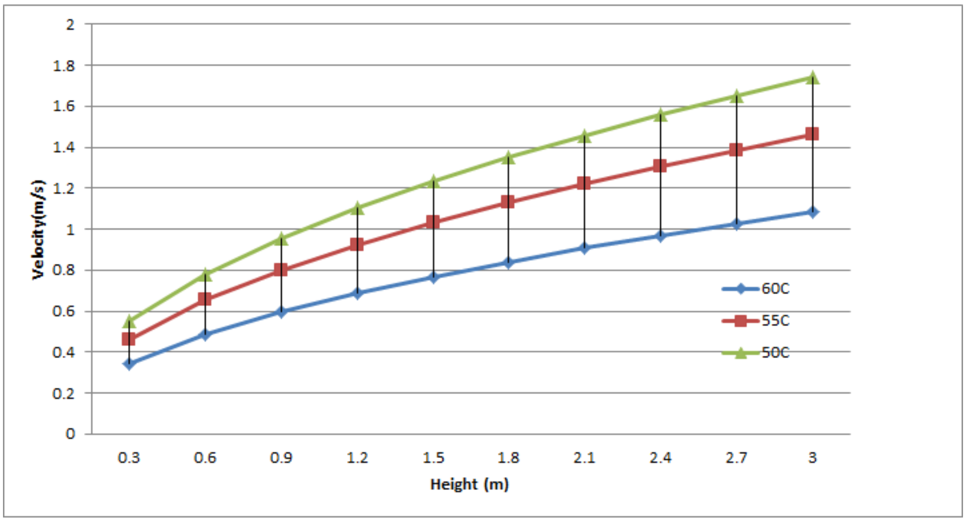

Figure 6. Air velocity in the solar cooling chimney with respect to the height of solar cooling chimney

Figure 7 illustrates the predicted surface temperature of photovoltaic panel attached with solar cooling chimney. These temperature values are determined using the velocity of air predicted in the earlier section. The natural draft in the duct will pull the ambient air from the bottom of the duct. Ambient air in this case is considered to be at 20 °C, which will flow over the back heated surface of the photovoltaic panel with the predicted velocity. This will cause the convection heat transfer from the photovoltaic panel. Nusselt number correlation for forced convection with either laminar or turbulent flow (Whitaker, 1972) is used to determine the convection heat transfer coefficient. Further the convection heat transfer coefficient along with Newton's law of cooling is used to predict the temperature of the photovoltaic panel. The temperature of the photovoltaic panel goes on reducing as the chimney height increases. This can be justified from the earlier graph in Figure 7, since the velocity of air increases it will increase the convection heat transfer coefficient reducing the temperature of the photovoltaic panel.

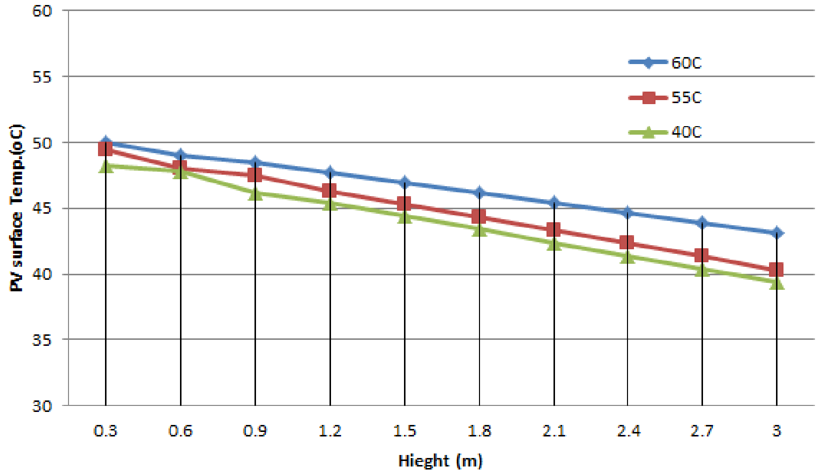

Figure 7. Predicted PV panel surface temperature with respect to change in height of solar cooling chimney

Figure 8 illustrates the improved voltage from the PV panel due to reduced surface temperature. As the solar cooling chimney height goes on increasing the output voltage from the PV panel will increase. In addition improving voltage will follow the outlet air velocity trend.

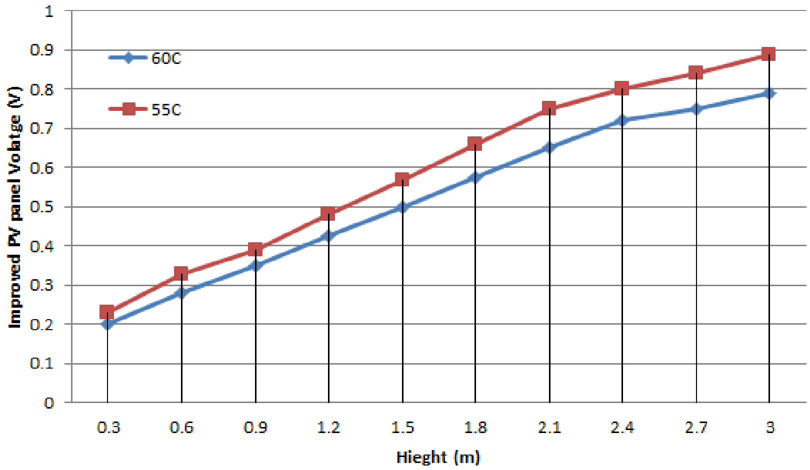

Figure 8. Effect of negative temperature coefficient on open circuit voltage of the PV panel

From above operation conditions, there is an optimum working temperature mentioned to achieve the said open circuit voltage. As the operating temperature of the PV panel goes on increasing the open circuit voltage will drop. This will reduce the efficiency of the PV panel as well.

5. Conclusion

The natural air draft that is achieved by buoyancy effects in a chimney can be used as a passive cooling medium for PV panels. Simple modification in the design of the system and including the additional absorber section can help to improve the induced natural draft of air and as a result helps improve the performance of the PV panel. Simple and preliminary analysis shows that by coupling the solar cooling chimney with a PV panel we can achieve considerable cooling of the PV panel and improve the efficiency of the PV panel. Taller chimneys can increase the velocity of air and further reduce the working temperature of PV panel to make it more efficient. Although taller chimneys will increase the overall cost of the system and reduce the simplicity in design. Taller chimney will also have a shading effect in case of PV panels are placed close to each other. Solar cooling chimney height should be optimized for the cost effectiveness and shading effect. Another way to improve the cooling / heat removal would be by increasing the surface area of the absorber section. Further investigation is required to accurately measure velocity of induced natural draft.

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