

Effect of Temperature and Electrode Thickness on the Performance of Dye-Sensitized Solar Cells

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(Received 4 June 2021, Accepted 13 August 2021)

The temperature and the electrode thickness are among the important parameters which affect the performance of photovoltaic cells. Based on a diffusion model defined in the literature, these effects have been investigated by using MATLAB. This model is mainly characterized by the diffusion of electrons in the semiconductor porous film (TiO_2). As a result, the increase of temperature has no effect on the density of the photocurrent. Moreover, when the thickness increases, the current density increases but after a certain value ($15 \mu\text{m}$) it decreases. The increase of the thickness results to a decrease in power and fill factor (FF), due to the internal resistance of the cell. In addition, the power conversion efficiency (PCE) is proportional to the temperature, as well as the thickness, except that the PCE starts to decrease from a certain value of the thickness ($d = 5 \mu\text{m}$). The simulation shows that the optimal electrode thickness is $5 \mu\text{m}$.

Keywords: Temperature, Electrode, MATLAB, Dye-sensitized solar cells

INTRODUCTION

Photovoltaic energy is an important solution for durable and environmentally friendly development; it contributes to reducing the large-scale consumption of fossil fuels [1]. Conventional photovoltaic cells are very efficient, although the manufacturing process is expensive and complicated. Thus, their use is quite restricted. Numerous investigations have been carried out to provide inexpensive photovoltaic cells with high power conversion efficiency (PCE) as dye sensitized solar cells (DSSCs) [2]. DSSC has numerous advantages including ecological, economical, and easy to produce. It usually consists of two electrodes, a photoelectrode and a counter-electrode, respectively. The first electrode is built from the semiconductor material (TiO_2) deposited on the transparent conductive oxide (TCO) substrate. The second electrode, which is a counter-electrode, is made from Pt coated on the TCO. Thereafter, the iodide/triiodide electrolyte (I^-/I_3^-) is filled between the two electrodes [3].

During the last few years, a significant number of research studies have been carried out on novel materials and modeling to elucidate the processes operating in the DSSCs [4-7].

A steady-state mathematical model based on the diffusion of electrons in the TiO_2 has been carried out to achieve an explicit photocurrent formulation, which has provided an understanding of the DSSC process [4]. This model has been used to examine the effect of open-circuit voltage on the thickness of the TiO_2 film [5]. Under lateral substrate-electrode illumination, for sufficiently thin films, the model shows a reduction in the open-circuit voltage for thicker films and a steady photovoltaic voltage for heavier films. Under lateral electrode-electrolyte illumination, the model forecasts a constant reduction of the voltage as the thickness of film rises, for sufficiently thick films a steady photovoltage was achieved [5].

The impact of thickness electrode on the maximum power point (MPP) has been investigated in the literature [6]. It has been observed that the open circuit voltage reduced as the electrode thickness became thinner. The optimal thickness of the electrode is $5 \mu\text{m}$ for the maximum

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MPP.

The aim of this work is to contribute to these activities by predicting the performance of the DSSC *via* the theoretical approach according to the parameters and internal parameters that improve its performance. The method is established on the analysis of the photoelectrochemical behavior of the DSSC based on the electron scattering process [4,5], in order to evaluate the effect of temperature and electrode thicknesses on photocurrent density-photovoltage (J-V) properties, power, FF and PCE.

DIFFUSION MODEL

This work is based on the equations that describe the functioning of the DSSC. These equations have been modeled in MATLAB, by integrating internal DSSC parameters into the programming. The modeling consisted in simulating the variation of J-V performance, power, and PCE as a function of temperature and thickness of the DSSC electrode. The theoretical study of photoelectrochemical activity in DSSC has been performed in the literature [4]. The resulting equation for electron recombination, the electron transport, and the electron photogeneration in DSSC are given by the following continuity equation

$$\frac{\partial n}{\partial t} = \frac{1}{e} \frac{\partial J}{\partial x} + G - R \quad (1)$$

where n is the electron density under illumination, J is the current density in the film. R and G are the recombination rate and the generation of carrier rate and, respectively. The generation rate may be expressed as follows in the TiO_2 film

$$G = \phi \alpha \exp(-\alpha x) \quad (2)$$

where ϕ is the flux of incident photons and α is the coefficient of absorption depending on the wavelength of the film sensitized by the dye. Across the film, the dye concentration is identical. The recombination is expected to be related to the concentration of the electron and may be expressed as:

$$R = \frac{(n - n_0)}{\tau} \quad (3)$$

where n_0 is the density of electron in the dark and τ is the lifetime of electrons independent of the position. Drift and scattering of electrons may participate in the density of current as follows:

$$J = en\mu_n \frac{\partial \Gamma}{\partial x} + eD \frac{\partial n}{\partial x} \quad (4)$$

where μ_n is the electrons mobility, D is the coefficient of diffusion of electrons, and Γ is the electric potential of the film. Whereas the particles size of TiO_2 is small to support energy of significant binding, the current density should be dominated by the scattering term. In the TiO_2 film, the reconfiguration of the electrons would result in an electrical field that is not connected to the binding energy of the individual particles.

The electric field in the TiO_2 thin film may be ignored at a relatively low light intensity where the electron density is not high. The time-dependent electron transport equation is given by substituting Eq. (4) into Eq. (1). The continuity equation in the lack of electron migration can be written as:

$$D \frac{\partial^2 n(x,t)}{\partial x^2} - \frac{\partial n(x,t)}{\partial x} - \frac{n(x,t) - n_0}{\tau} + \phi \alpha \exp(-\alpha x) = 0 \quad (5)$$

The first two terms describe the movement of electrons and the change of electron concentration across time, respectively. The third term reflects the recombination rate and the time constant that characterizes it (τ). The fourth term is the injection of electron rate from the mechanism of photoexcitation. The Eq. (5) is solved by Fourier transform and variables separation.

Under steady-state conditions and according to the model described in [4], the steady-state of photocurrent is symmetrical to the intensity of light, consequently, the Eq. (5) becomes

$$D \frac{\partial^2 n(x)}{\partial x^2} - \frac{n(x) - n_0}{\tau} + \phi \alpha \exp(-\alpha x) = 0 \quad (6)$$

where $n(x)$ is the excess concentration in the film of photo-generated electrons evaluated at the interface of TiO_2/TCO ,

n_0 is the electrons concentration in the circumstances of equilibrium in the dark conditions, τ is the lifetime of free electrons in the conduction band, D is the electron diffusion coefficient, ϕ is the flux of incident photons and α is the porous film's light absorption coefficient.

The Eq. (6) has not taken into consideration the probability of trapping electrons, since it is only relevant under unstable conditions. The electrons are quickly collected as a photocurrent through short-circuit conditions and none of the electrons are attracted directly onto the counter-electrode. Hence, the two boundary conditions are:

$$n(0) = n_0 \quad (7)$$

$$\left(\frac{dn}{dx}\right)_{x=d} = 0 \quad (8)$$

where d is the thickness of electrode. It was, therefore, possible to achieve the short-circuit current density (J_{sc}) by using the following form:

$$J_{sc} = \frac{e\phi L\alpha}{1-L^2\alpha^2} \left[-L\alpha + \tanh\left(\frac{d}{L}\right) + \frac{L\alpha e^{-d\alpha}}{\cosh\left(\frac{d}{L}\right)} \right] \quad (9)$$

e is the electron charge (1.60218×10^{-19} C) is the length of diffusion of electrons provided by:

$$L = \sqrt{D\tau} \quad (10)$$

DSSCs work under the potential difference V between the level of Fermi (TiO_2) and the electrolyte redox potential, then the electron density at the interface of TiO_2/TCO ($x = 0$) rises to n , providing a new boundary condition

$$n(0) = n \quad (11)$$

The condition is unchanged at $x = d$, as can be seen in Eq. (8). The correlation between J and V is given by the resolving Eq. (6)

$$V = \frac{KTm}{e} \ln \left[\frac{L(J_{sc} - J)}{eDn_0 \tanh\left(\frac{d}{L}\right)} + 1 \right] \quad (12)$$

where m is the ideality factor and K is a constant of Boltzmann equal to 1.38066×10^{-23} J K⁻¹.

RESULTS AND DISCUSSION

Photovoltaic energy is strongly dependent on temperature. In terrestrial environments, the photovoltaic cells are typically exposed to operating temperatures between 283.15 K and 328.15 K. The typical factors of the photovoltaic cell, *i.e.*, current density (J), power, FF, and PCE are affected by temperature and electrode thickness. To investigate the relationship of such factors with temperature and electrode thickness, we have done the modeling by taking the value of the light intensity as 10^{17} cm⁻² s⁻¹ which represents 1 sunshine condition 1000 W m⁻², as well as the internal parameters in the DSSC which were obtained from the previous work (Table 1).

The J-V properties of the DSSCs at various temperatures and electrode thicknesses are shown in Fig. 1. As shown in Fig. 1, the rise in temperature does not affect the density of photocurrent J . Nevertheless, various electrode thicknesses provide different values of J . The thicknesses 1 μm , 5 μm , 10 μm , 15 μm and 20 μm yield current density values of 6.3 mA cm⁻², 14.54 mA cm⁻², 15.44 mA cm⁻², 15.3 mA cm⁻² and 15.12 mA cm⁻², respectively. We find that once the thickness rises, the current density increases, but beyond 15 μm the density reduces. A thinner electrode can thus absorb more photons, which leads to a greater density value of the current. Nonetheless, if the electrode of thickness is higher than the

Table 1. DSSC Internal Parameters and Factors Used in the Analysis

Parameters	Values	Ref.
Electronic density in the dark n_0 (cm ⁻³)	10^{16}	[8,9]
Electron lifetime τ (ms)	10	[5,10]
Electron diffusion coefficient D (cm ² s ⁻¹)	5×10^{-4}	[11]
Light intensity ϕ (cm ⁻² s ⁻¹)	10^{17}	[5,12]
Absorption coefficient α (cm ⁻¹)	5000	[5,12]
Ideality factor	4.5	[5,12]

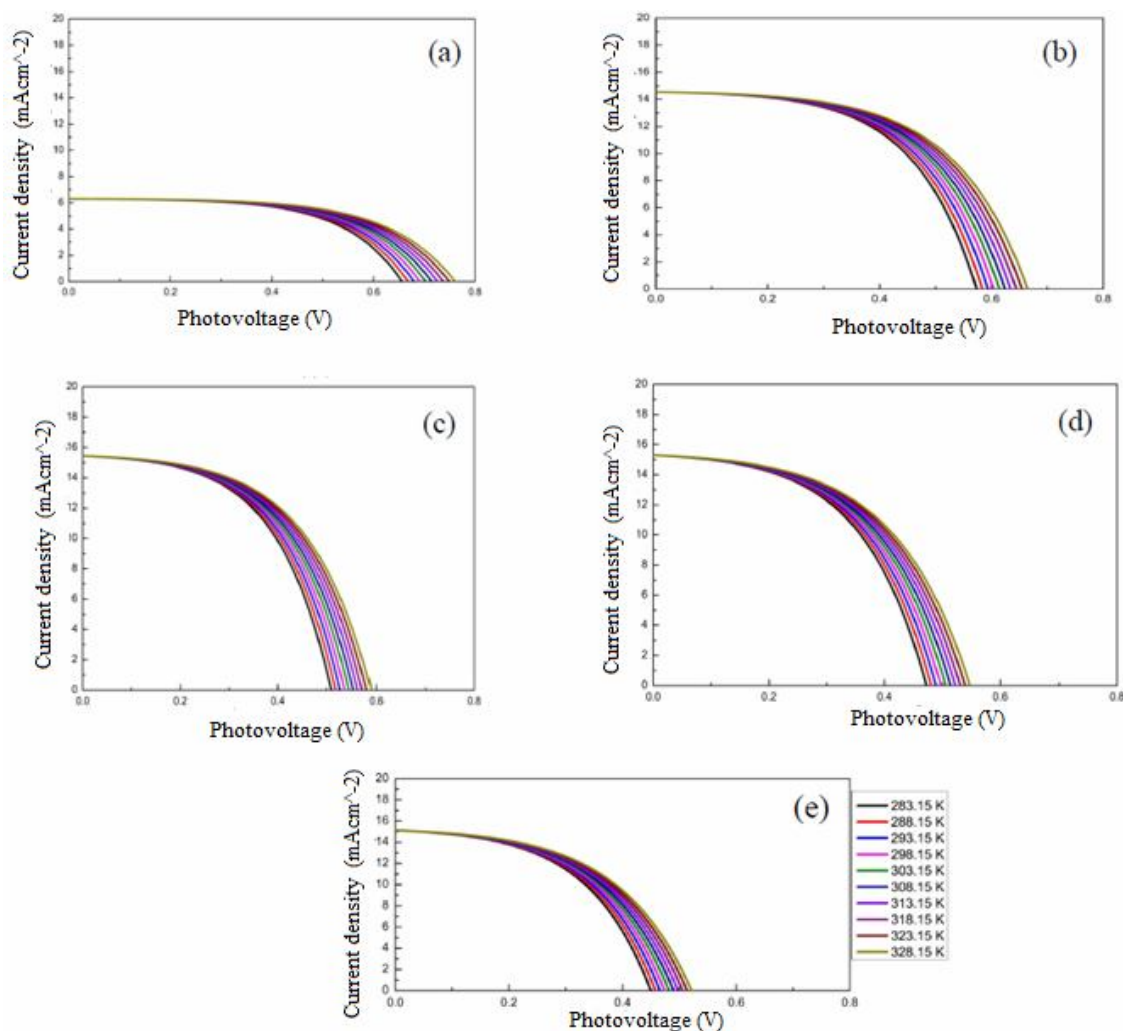


Fig. 1. Variation of DSSC J-V characteristic under different temperatures and different electrode thicknesses: (a) $d = 1 \mu\text{m}$, (b) $d = 5 \mu\text{m}$, (c) $d = 10 \mu\text{m}$, (d) $d = 15 \mu\text{m}$ and (e) $d = 20 \mu\text{m}$.

depth of penetration of the light, the photons numbers useful for the electrons photogeneration will attract the limit that produces more recombination that leads to greater electron loss, and therefore a gradual reduction in current density. The power properties *versus* voltage with various temperatures and electrode thicknesses are illustrated in Fig. 2. As presented in Fig. 2, electrode thicknesses affect the power.

For $T = 328.15 \text{ K}$, the electrode thickness $1 \mu\text{m}$ gives a maximum value of power 2.94 mW cm^{-2} , thickness $5 \mu\text{m}$

yields a maximum value of power 5.63 mW cm^{-2} , thickness $10 \mu\text{m}$ gives 5.07 mW cm^{-2} , thickness $15 \mu\text{m}$ gives 4.51 mW cm^{-2} and thickness $20 \mu\text{m}$ gives 4.16 mW cm^{-2} . We notice that the power reduces with the increase of electrode thickness, which means that the internal resistance of the cell rises. The optimal power achieved by this approach is suitable for the electrode thickness of $5 \mu\text{m}$. Figure 3 shows the variations of FF with electrode thicknesses at a given temperature. The FF decreases as the thickness of the electrode increases, revealing an increase in the internal

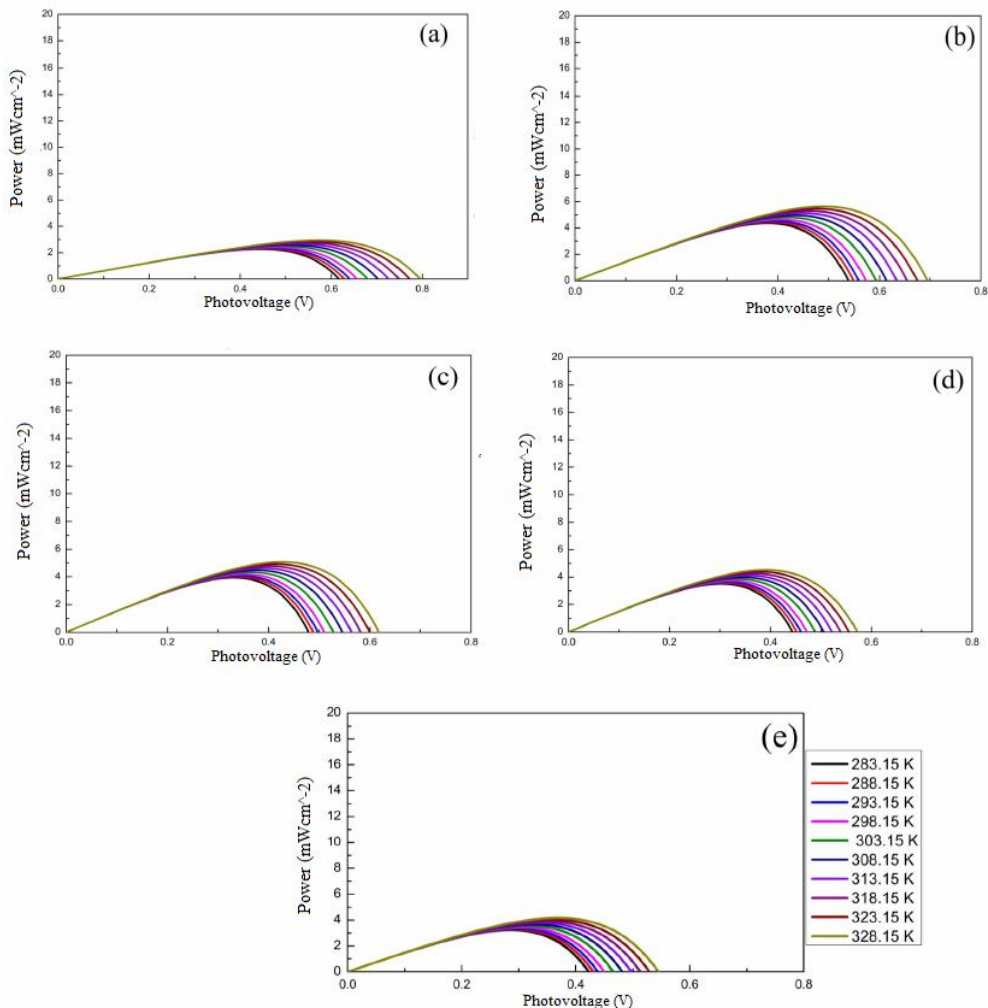


Fig. 2. Variation of the power under different temperatures and different electrode thicknesses: (a) $d = 1 \mu\text{m}$, (b) $d = 5 \mu\text{m}$, (c) $d = 10 \mu\text{m}$, (d) $d = 15 \mu\text{m}$ and (e) $d = 20 \mu\text{m}$.

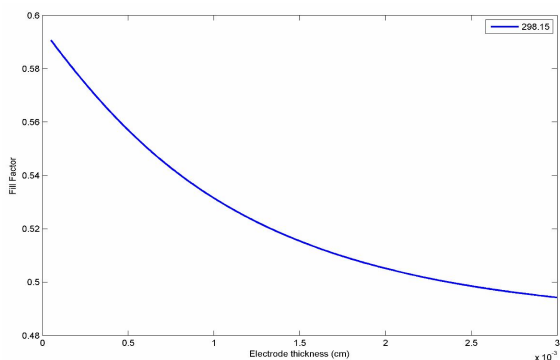


Fig. 3. Effect of electrode thicknesses on Fill factor at a given temperature.

resistance of DSSC.

Figure 4 presents the variation of FF with the temperature at different electrode thicknesses. The electrode thickness $1 \mu\text{m}$ gives a maximum value of FF 0.5865, thickness $5 \mu\text{m}$ gives 0.557, thickness $10 \mu\text{m}$ gives 0.5315, thickness $15 \mu\text{m}$ gives 0.5154, and thickness $20 \mu\text{m}$ gives 0.5051. The electrode thickness of $5 \mu\text{m}$ provides the best FF value.

The effects of temperature and electrode thickness on PCE are presented in Fig. 5 and Fig. 6. The electrode

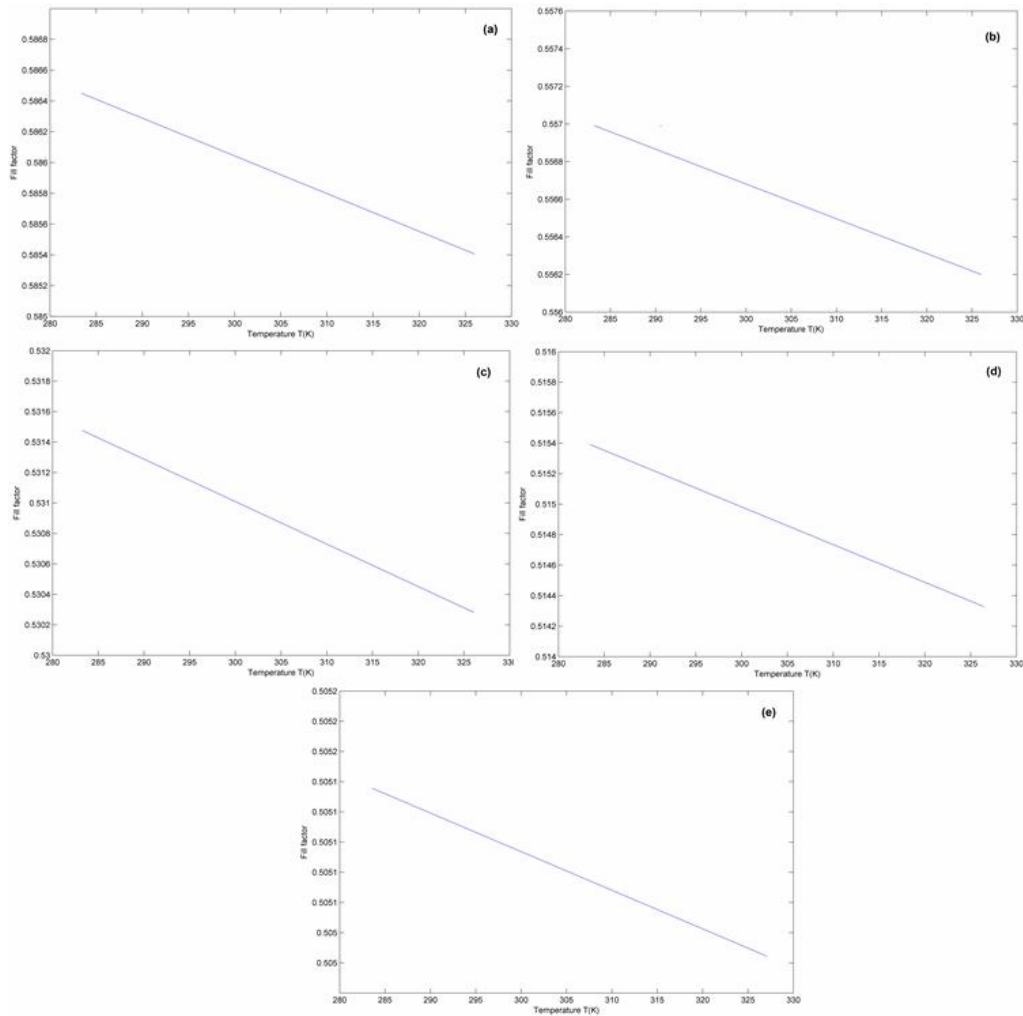


Fig. 4. Effect of temperature on Fill factor at different electrode thicknesses: (a) $d = 1 \mu\text{m}$, (b) $d = 5 \mu\text{m}$, (c) $d = 10 \mu\text{m}$, (d) $d = 15 \mu\text{m}$ and (e) $d = 20 \mu\text{m}$.

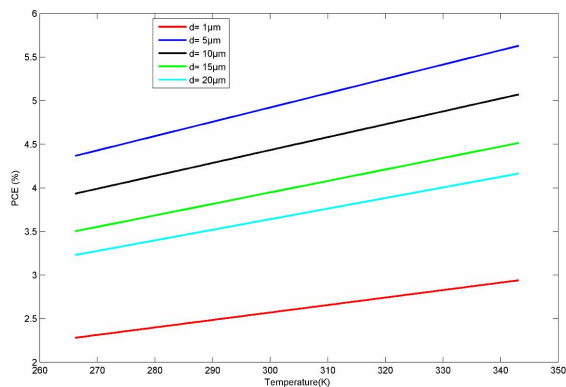


Fig. 5. Effect of temperature on power conversion efficiency with different electrode thicknesses.

thickness of $1 \mu\text{m}$ has the lowest PCE. We further observe that the PCE is proportional to temperature and thickness, except that the PCE starts to decrease from the value of the thickness ($d = 5 \mu\text{m}$). This is defined in the characteristic of power vs. voltage. The electrode thickness of $5 \mu\text{m}$ provides the best PCE values as a function of temperature.

The combination of variations in current density, power, and PCE implies that the electrode thickness of $5 \mu\text{m}$ provides optimal results. Our result is in agreement with those of Meng *et al.* which presented a study on the effect of electrode thickness on the MPP by varying the electron diffusion coefficient, the incident photon flux, the light

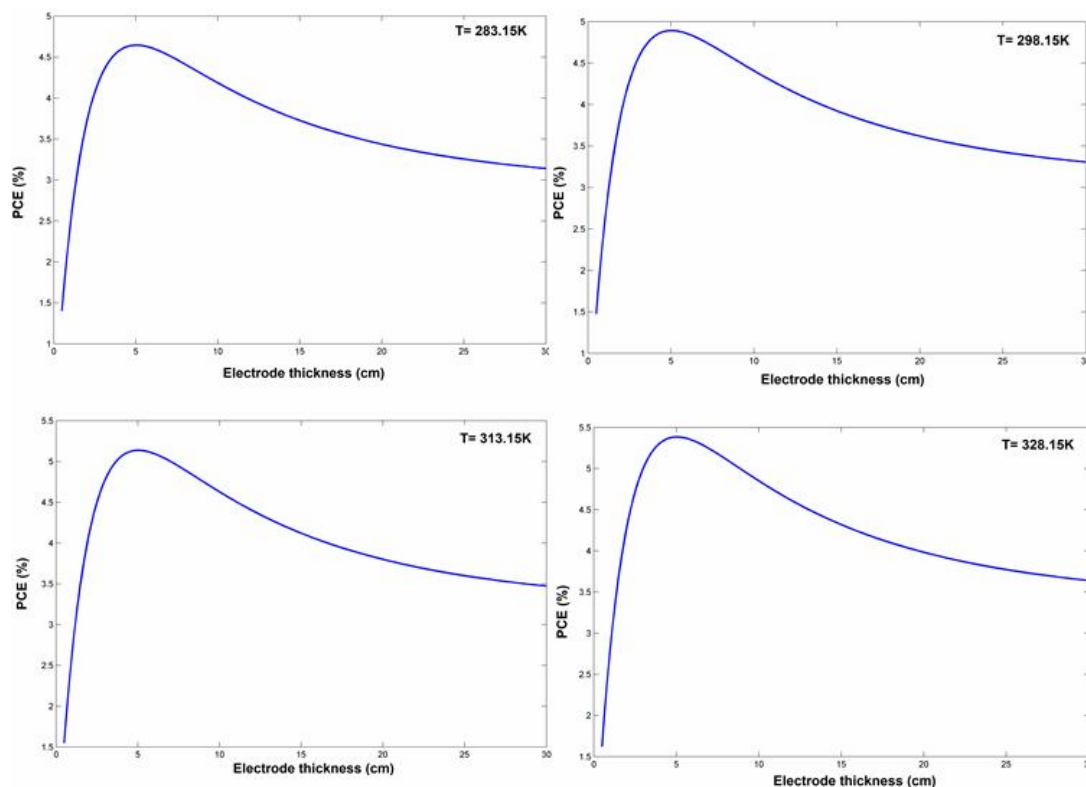


Fig. 6. Effect of electrode thicknesses on power conversion efficiency at a given temperature.

absorption coefficient, and the ideality factor [6].

CONCLUSIONS

In this work, the performance of the DSSC has been simulated via a theoretical analysis based on the factors and internal parameters that enhance its performance. This analysis has been achieved by analyzing the photoelectrochemical behavior of the DSSC based on the diffusion of electron process, in order to investigate the effect of temperature and electrode thicknesses on J-V properties, power, and PCE. We have found that the rise in temperature does not affect the density of photocurrent J. On the other hand, as the thickness increases, the current density increases but from a certain value (15 μm) it starts to decrease. We have mentioned that the increase in thickness leads to a decrease in power and FF. We have noted that the PCE is proportional to the temperature, the

same as the thickness, except that the PCE starts to decrease from a certain value of the thickness ($d = 5 \mu\text{m}$).

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