

Research Article

Optimization of Water based Optical Filter for Concentrated Crystalline Si PV/T System - A Theoretical Approach

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Abstract

Optical filters are widely used in cameras, electronics, lighting and optical sensors, etc. In this paper, we have optimized water-based optical filter for Hybrid Solar Photovoltaic/Thermal (PV/T) System. The study demonstrates that water can be used effectively as optical filter for concentrated PV/T systems.

Keywords: Optical Filter, Solar Photovoltaic System, Solar Thermal System, Solar Spectrum, Absorption Coefficient.

Introduction

Some part of the incident solar energy on solar cell is converted into the electrical energy and the rest is converted into thermal energy, which increases the temperature of the solar cell. The rise in the temperature of the solar cell reduces the solar cell efficiency by -0.0045 % per °C (F. Sarhaddi *et al*, 2011).

The efficiency of the PV systems can be increased by withdrawing the thermal energy of the module. Such systems are commonly known as hybrid photovoltaic thermal (PV/T) systems. There are various methods available for withdrawing the thermal energy from the solar cell. Even water and air can be used for heat extraction. PV heating is mainly the result of the absorbed solar radiation that is not converted into electricity and cooling of photovoltaic cells is considered necessary to keep electrical efficiency at a satisfactory level.

For cooling the PV system, putting of the working fluid directly in contact with PV system and thereby removing excess heat, is one option. This type of design necessitates a compromise between the drops in efficiency with temperature of PV cell due to value of higher output temperature from the thermal system. While straightforward integrated system forces operation temperatures to be moderate, in the range of 30-100 °C, in concentrating solar PV/T systems, irradiance on the receiver is high causing the compromise in performance to be even more pronounced (Robert A Taylor *et al*, 2012). This paper suggests that water as optical filter can provide one possible solution to the challenges discussed above. In this work, we have tried to optimize the thickness of the water as an optical filter before the solar radiation incident on photovoltaic module.

Many hybrid solar PV/T systems have been designed with optical filters. Most of the optical filters are made of solid

materials or thin coating of materials. These optical filters are used for the camera, electronics, lighting and optical sensors, etc. However, not many efforts have been made for optical filters in solar PV/T systems.

Solar spectrum has 4.62% UV, 53.85% VIS and 41.53% IR. The crystalline solar cell uses some part of UV, all parts of visible and some part of IR. The crystalline solar cell quantum efficiency is in between 300 nm to 1180 nm wavelength of solar light which contains about 86% of energy of the total solar energy of the solar spectrum, the rest of energy is converted in to heat which increases the temperature of the solar PV cell. So, it is required to filter out the wavelength above the 1180 nm of the solar spectrum.

The aim of this study is that we use water as an optical filter for solar spectrum and remove the IR part of the solar spectrum, which causes the heating of the solar cell. The concentrated solar radiation falls on the optical filter and IR component gets absorbed by the water, and then falls on the crystalline PV cell shown in Figure 1.

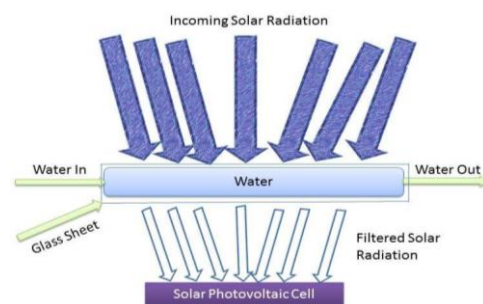


Figure 1: Working of Optical Filter

Quantum efficiency of crystalline solar cell

The silicon solar cell has band gap of 1.12 eV, So, ideally below the band gap (above the 1100 nm wavelength), the

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photons have not enough power to move electrons from valance band to conduction band. Si is an indirect band gap semiconductor, so, there is not a sharp cut-off at the 1100 nm wavelength. The quantum efficiency of a silicon solar cell under glass at short wavelength below 300nm is almost zero, since the glass absorbs most of the light. At intermediate wavelengths, the cell approaches the ideal. At long wavelength (1190 nm) the quantum efficiency fall back to zero as shown in Figure 2.

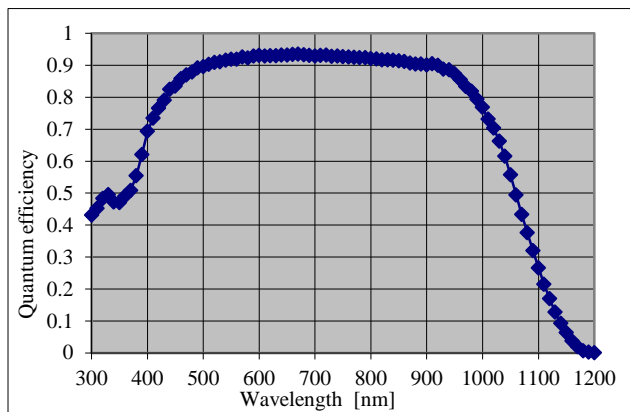


Figure 2: Quantum Efficiency of Si Solar Cell

Absorption and penetration of electromagnetic radiation

It is of interest in this work to define the transmittance, absorbance and Beer’s Law in relation to electromagnetic radiation as follows:

Transmittance

Transmittance of medium is the ratio of transmitted intensity of light and incident intensity of light. The Transmittance (T) is defined by the equation:

$$T = (I/I_0) \tag{1}$$

Absorbance

Absorbance (A) is the amount of light absorbed by a substance.

$$A = - \log_{10} (I/I_0) \tag{2}$$

Absorption Coefficient

Absorption coefficient determines how far into a material light of a particular wavelength can penetrate before it is absorbed.

Absorption coefficient a_λ (cm^{-1}) is related to the extinction coefficient k by the relation given below:

$$a_\lambda = \frac{4\pi k}{\lambda} \tag{3}$$

Beer’s Law

The Beer’s Law states that the intensity of an electromagnetic radiation penetrating a material falls off exponentially with distance from the surface.

$$A = \epsilon_\lambda cL \tag{4}$$

From Equation (2) and (4)

$$\epsilon_\lambda cL = -\log_{10} (I/I_0)$$

$$\epsilon_\lambda = a_\lambda / 2.303*c \tag{5}$$

$$-a_\lambda L = 2.303 \log_{10} (I/I_0)$$

$$-a_\lambda L = \log_e (I/I_0)$$

$$I = I_0 e^{- (a_\lambda L)} \tag{6}$$

where,

I = Transmitted intensity of light (W/m^2)

I_0 = Incident intensity of light (W/m^2)

L = Path length (cm)

ϵ_λ = Molar absorptivity ($liters*mole^{-1}*cm^{-1}$)

c = Molar concentration (mole)

Transmission through soda-lime glass 3 mm thick

As shown in Figure 1, the incoming solar radiation passes through the rectangular-tube of soda-lime glass of approximately 3 mm thickness before penetrating the water.

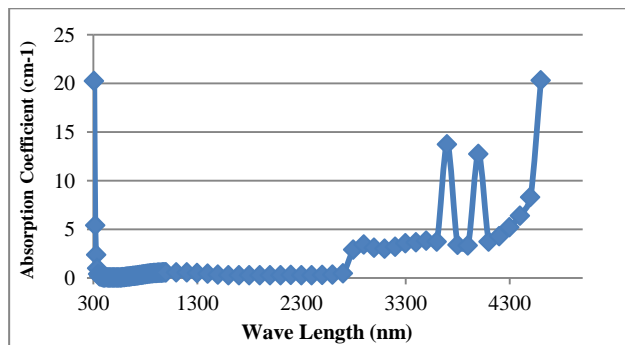


Figure 3: Absorption Coefficient (cm^{-1}) of Soda-lime Glass

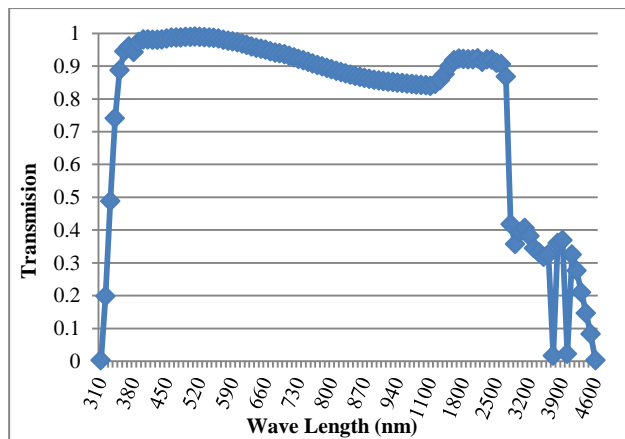


Figure 4: Transmission of Soda-lime Glass (3mm thickness)

So, it is important for us to consider the transmission property of soda-lime glass of 3 mm thickness. The absorption coefficient of soda lime glass (M. Rubin, 1985; E.D Palik, 1985) is given in Figure 3 and transmission of 3 mm soda-lime glass is given in Figure 4. From the Figure 4, it may be inferred that the wavelengths below 300 nm do not pass through the glass. Similarly, the wavelengths beyond about the 4600 nm are not crossing the 3 mm thickness soda-lime glass.

Water absorption property

Water is almost transparent to the visible light and almost opaque for IR wavelengths.

From the data given by other researchers researchers (G. M. Hale et al, 1973), it may be seen that the absorption coefficient of water has not much significant variation for wavelengths above 1500 nm.

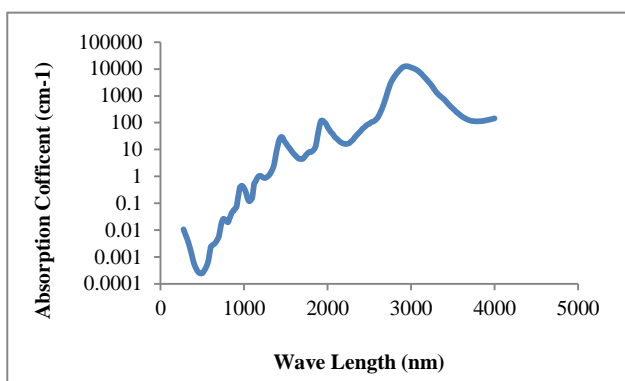


Figure 5: Water Absorption Coefficient

In this work, we have studied the variation of solar radiation spectrum (Gueymard C, 2004; Gueymard C et al, 2002) without filtering in water, with filtering from water and quantum efficiency of crystalline Si solar cell for different thicknesses of water namely, 0.25 cm, 0.50 cm, 0.75 cm, 1.00 cm, 1.25 cm, 1.50 cm, 1.75 cm 2.00 cm, 2.25 cm and 2.50 cm. The variation of unfiltered solar spectrum, filtered solar spectrum for various thicknesses of water from 0.25 cm to 2.00 cm and quantum efficiency are given in Figures 5 to 12.

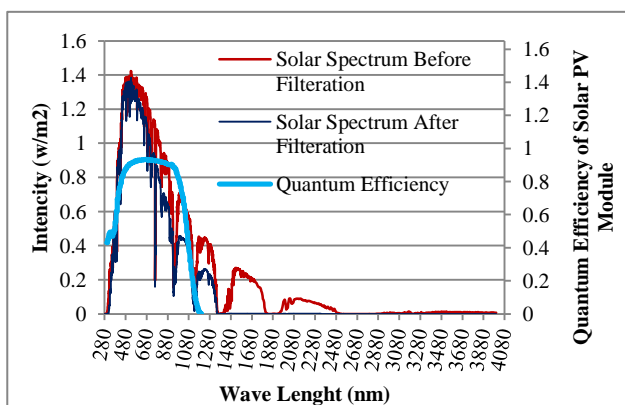


Figure 5: Comparison of Solar Radiation with Quantum Efficiency of Solar PV Module before Filtration and after Filtration at 0.25 cm Water Depth

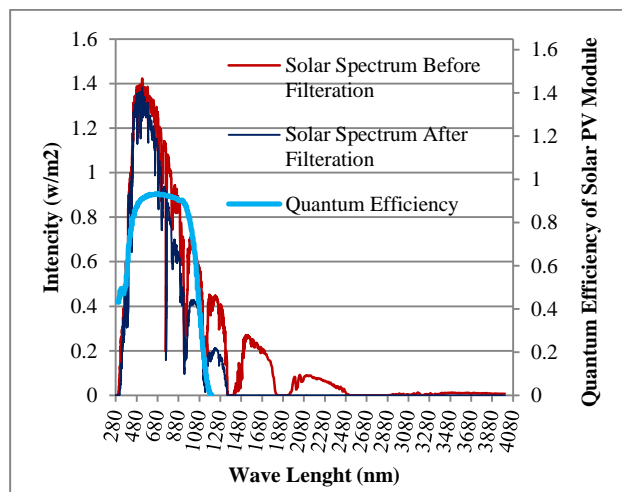


Figure 6: Comparison of Solar Radiation with Quantum Efficiency of Solar PV Module before Filtration and after Filtration at 0.50 cm Water Depth

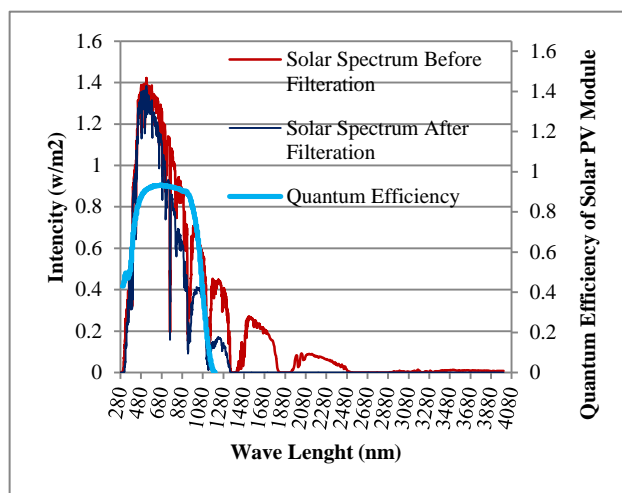


Figure 7: Comparison of Solar Radiation with Quantum Efficiency of Solar PV Module before Filtration and after Filtration at 0.75 cm Water Depth

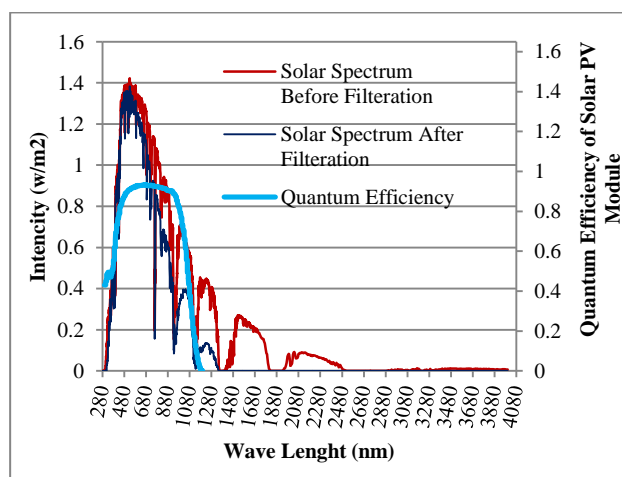


Figure 8: Comparison of Solar Radiation with Quantum Efficiency of Solar PV Module before Filtration and after Filtration at 1.00 cm Water Depth

Table 1: Direct Solar Energy Spectral distribution of Energy (Air Mass 1.5)

Range of Wavelength	Energy available (W/m ²)	Percent of Energy (%)
Energy in between 280 - 300 nm	0.001	0.0001
Energy in between 300 - 1190 nm	766.97	86.41
Energy in between 1190 - 4000 nm	120.67	13.59
Total	887.64	100

Table 2: Direct Solar Energy after Water Filtration inclusive of Upper and Lower Glass Effect

Depth of water (cm)	Energy in between 280 - 300 (nm)		Energy in between 300 - 1190 (nm)		Energy in between 1190 - 4000 (nm)		Total Energy available for SPV Module (W/m ²)
	Energy available for SPV Module (W/m ²)	Percent of Energy Absorbed (%)	Energy available for SPV Module (W/m ²)	Percent of Energy Absorbed (%)	Energy available for SPV Module (W/m ²)	Percent of Energy Absorbed (%)	
0.00	0	100*	656.22	14.44*	94.51	21.68*	750.73
0.25	0	100*	646.98	15.65**	31.86	73.60**	678.84
0.50	0	100*	638.75	16.72**	24.34	79.83**	663.09
0.75	0	100*	631.37	17.68**	18.71	84.50**	650.08
1.00	0	100*	624.70	18.55**	14.44	88.04**	639.14
1.25	0	100*	618.62	19.34**	11.17	90.74**	629.79
1.50	0	100*	613.05	20.07**	8.67	92.81**	621.72
1.75	0	100*	607.92	20.74**	6.75	94.41**	614.67
2.00	0	100*	603.17	21.36**	5.26	95.64**	608.43
2.25	0	100*	598.74	21.94**	4.11	96.60**	602.85
2.50	0	100*	594.60	22.48**	3.21	97.34**	597.81

*Due to upper and lower glass, **Due to upper and lower glass and water

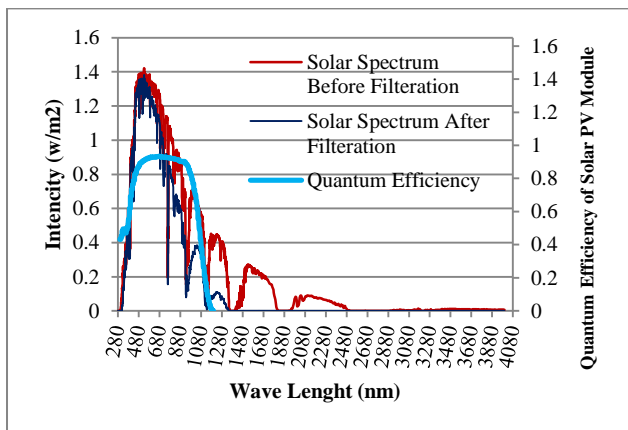


Figure 9: Comparison of Solar Radiation with Quantum Efficiency of Solar PV Module before Filtration and after Filtration at 1.25 cm Water Depth

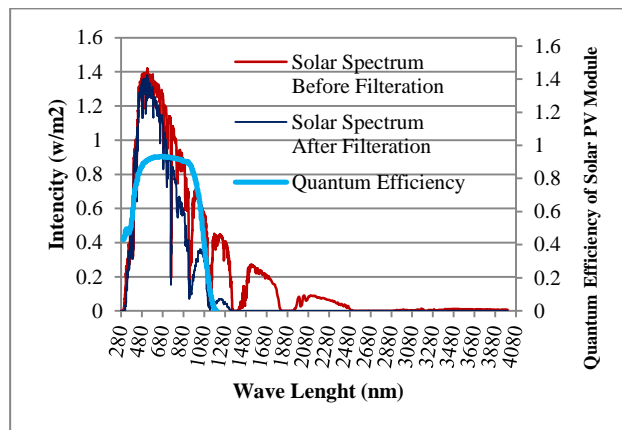


Figure 11: Comparison of Solar Radiation with Quantum Efficiency of Solar PV Module before Filtration and after Filtration at 1.75 cm Water Depth

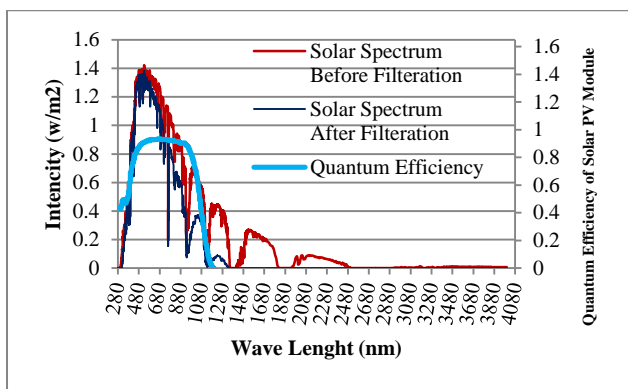


Figure 10: Comparison of Solar Radiation with Quantum Efficiency of Solar PV Module before Filtration and after Filtration at 1.50 cm Water Depth

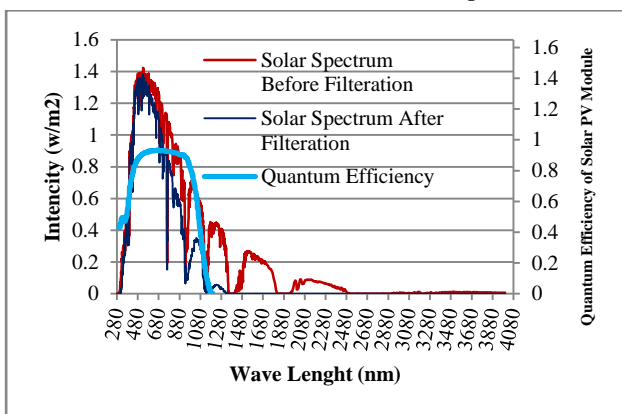


Figure 12: Comparison of Solar Radiation with Quantum Efficiency of Solar PV Module before Filtration and after Filtration at 2.00 cm Water Depth

Table 3: Variation of Energy Absorbed by the Glass and that of Water with different Depths of Water

Depth of Water (cm)	Energy absorbed by the Glass (%)	Energy absorbed by the Water (%)
0.25	13.35	10.17
0.50	12.70	12.60
0.75	12.16	14.60
1.00	11.70	16.29
1.25	11.32	17.73
1.50	10.98	18.98
1.75	10.69	20.06
2.00	10.43	21.03
2.25	10.20	21.88
2.50	9.99	22.66
2.75	9.81	23.36
3.00	9.64	24.01
3.25	9.48	24.60

Table 4: Percent of Energy available after the Filtration from the Glass and Water, which is available for Solar Photovoltaic Module in the Range of 300 nm and above

Depth of Water (cm)	Energy in the range of 300nm to 1190 nm (%)	Energy in the range of 1190 to above (%)
0.00	87.41	12.59
0.25	95.31	4.69
0.50	96.33	3.67
0.75	97.12	2.88
1.00	97.74	2.26
1.25	98.23	1.77
1.50	98.60	1.40
1.75	98.90	1.10
2.00	99.14	0.86
2.25	99.32	0.68
2.50	99.46	0.54
2.75	99.58	0.42
3.00	99.66	0.34
3.25	99.74	0.26

Discussion and results

The distribution of direct solar energy for air-mass 1.5 is given in Table 1.

Table 2 gives the data of direct solar energy after water filtration inclusive of upper and lower glass effect.

The variation of energy absorbed by the glass and that of water with different depths of water is given in Table 3.

The graphical representation of the data of Table 3 is depicted in Figure 13.

Percent of energy available after the filtration from the glass and water, which is available for solar photovoltaic module, is given in Table 4.

The graphical representation of the data given in Table 4 is depicted in Figure 15.

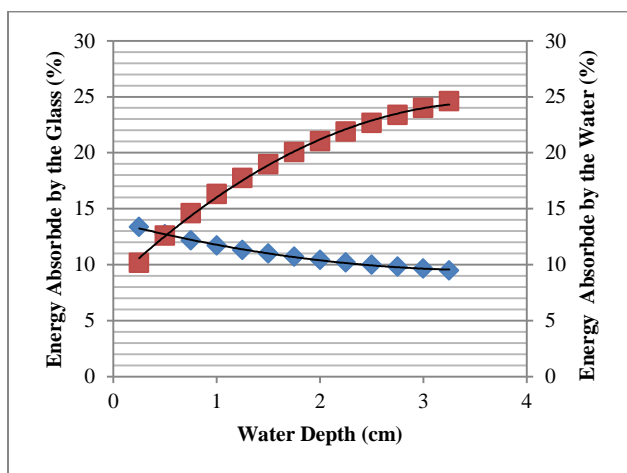


Figure 13: Variation of Energy Absorbed by the Glass and that of Water with different Depths of Water

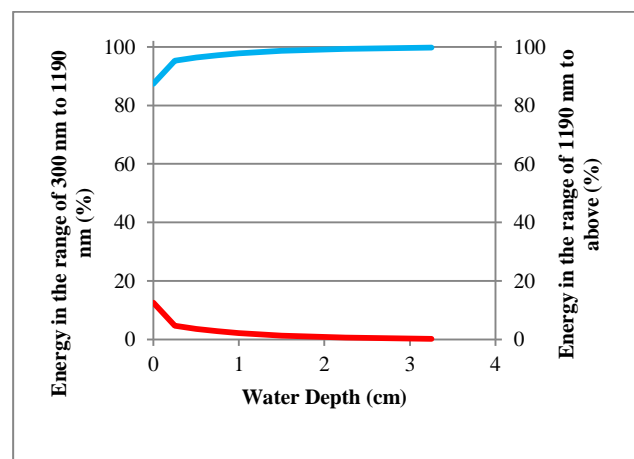


Figure 15: Percent of Energy available after the Filtration from the Glass and Water, which is available for Solar Photovoltaic Module in the Range of 300 nm and above

It is clear from above tables and curves that as we increase the depths of the water, the solar radiation on the side of the IR radiation get absorbed by the water which is more responsible for heating of the solar cell. The water also absorbs some part of the solar radiation below 1190 nm. If we further increase the depth of the water, the absorption above 1190 nm is not significant as shown in Figures 16 and 17, which represent water depth as 2.25 cm and 2.50 cm.

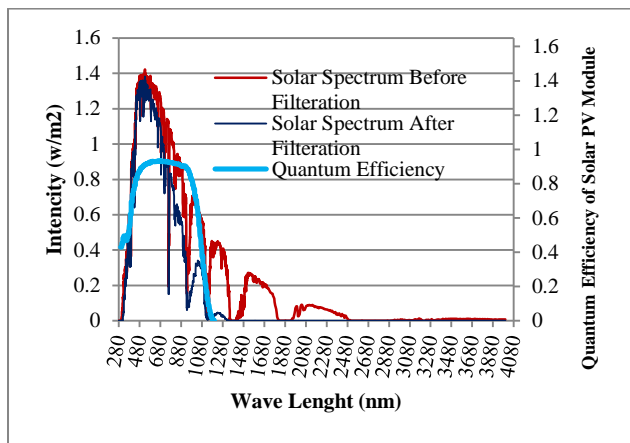


Figure 16: Comparison of Solar Radiation with Quantum Efficiency of Solar PV Module before Filtration and after Filtration at 2.25 cm Water Depth

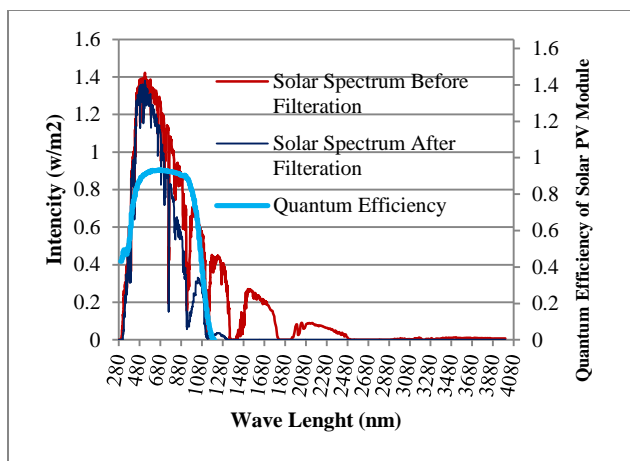


Figure 17: Comparison of Solar Radiation with Quantum Efficiency of Solar PV Module before Filtration and after Filtration at 2.50 cm Water Depth

It is clear from table 4 and figure 15 that 2.00 cm thickness of the optical filter is good for the crystalline Si solar cell because 99.14% of energy is available in the range of 300 nm to 1190 nm and only 0.86% of energy available in the range of 1190 nm and above. This matches with the quantum efficiency of the crystalline Si solar cell. Further increase of water thickness as an optical filter does not have significant absorption in the range 1190 nm and above.

Conclusion

Using of water, which is not a costly material in PV/T systems with concentration as an option for optical filter, is a good proposition as demonstrated in this work. The experimental setup for such a system has been fabricated using the depth of water as 2.00 cm. The experimental results are to be reported later.

The use of optical filters to utilize the incoming solar radiation’s energy for thermal use in PV/T system particularly, systems with concentration is a good option, which needs to be further researched and if economically viable, be used in such systems.

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