



Study on the Performance of Photogalvanic Cell for Solar Power Generation and Storage in Chlorophenol Red - Isopropyl alcohol -Sodium Lauryl Sulphate system

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Abstract: Rising concerns about climate change, the health effects of air pollution, energy security and energy access, along with volatile oil prices in recent decades, have led to the need to produce and use alternative, low-carbon technology options such as renewable. The photogalvanic cells as described in the present article are promising energy devices as they provide for a route for simultaneous solar power generation and its storage. The study of photogalvanic effect in Chlorophenol Red - Isopropyl alcohol - Sodium Lauryl Sulphate system has been observed in basic medium with aim of searching relatively proper combination of chemicals like photosensitizer, reductant and surfactant for further increasing the efficiency of these cells. This combination of chemicals has shown very impressive and surprisingly very high improvement in cell performance. The solar conversion efficiency, fill factor, cell performance (as $t_{1/2}$), power at power point, open circuit potential and equilibrium current at 10.4 mWcm^{-2} has been observed of the order of 2.240%, 0.2756, 165 min, 233.011 μW , 1150 mV and 735 μA respectively.

Keywords: Photogalvanic cell, Chlorophenol Red, Isopropyl alcohol, Sodium Lauryl Sulphate (NaLS), Photogalvanic effect (PGE), fill factor, power point, conversion efficiency.

Introduction:

Non-renewable Sources of electricity production such as coal, oil and natural gas have contributed to a third of the world's greenhouse gas emissions. It is important to raise the standard of living by providing clean and reliable electricity. Solar energy is universally available, decentralized, non-polluting, freely available energy source and essential for all forms of life. The Photogalvanic cell is an important tool in the process of converting solar energy into electrical energy. It is the third type of photoelectrochemical cell used to convert solar energy. In a photogalvanic cell two inert electrodes are used and the light is absorbed by the electrolyte, for example a dye solution. Electron transfer occurs between excited dye molecules and electron donors or acceptor molecules added to the electrolyte. A photovoltage between the two electrodes is developed if the light is absorbed by the electrolyte. Accordingly, the photogalvanic cell is essentially a concentration cell and is based on some chemical reaction, which gives rise to high energy products on excitation by a photon. This energy product loose energy electrochemically lead to generate the electricity called as a photogalvanic effect (PGE). First of all PGE was detected as action of Light on the Ferrous Iodine Iodide Equilibrium¹but systematically investigated in Thionine-Iron System²⁻³.The PGE in ferrous-thionine system has been found to be a complex function of various experimental parameters. It was found that maximum potential was 170mV (open circuit potential). The feasibility of employing this system for conversion of light into electricity has been investigated by many workers.⁴ Thionine has been condensed with poly (N-methylolacrylamide) to give a polymer-dye complex. Spectral and photogalvanic properties of the complex have been studied. Photogalvanic potential is found to depend strongly on the polymer-dye ratio.⁵ Photovoltage generation observed in Phenosafranine Dye-EDTA Sandwich Cell.⁶ A photogalvanic cell containing thionine and EDTA have used for solar energy conversion and storage. The photocurrent and photopotential generated by this cell were 80 μA and 900 mV respectively.⁷

PGE was studied in Methylene blue-EDTA-NaLS system. The photocurrent and photopotential observed in this system were 190 μA and 654 mV, respectively.⁸ Sodium lauryl sulphate (NaLS), tetradecyl trimethyl ammonium bromide (TTAB) and Brij-35 were used in a photogalvanic cell containing azur A as a photosensitizer and glucose as a reductant for solar energy conversion and storage.⁹ Photocurrent 70 μA and photopotential 315 mV observed in dye sensitized cell containing toluidine blue, glucose and tergitol-7 as a photosensitizer, reductant and surfactant, respectively.¹⁰ The photopotential 175 mV and photocurrent 35 μA were observed in CTAB-glucose-toluidine blue system. The conversion efficiency, maximum power and storage capacity were observed as 0.0578%, 6.26 μW and 6 min respectively.¹¹ The photogalvanic effect was studied in a photogalvanic cell containing EDTA, methylene blue + toluidine blue (mixed photosensitizers). The photopotential and photocurrent generated were 742.0 mV and 110.0 μA , respectively. The observed conversion efficiency was 0.5398 % and the maximum output of the cell was 81.62 μW . This cell can be used for 34.0 min in the dark.¹² Photogalvanic effect (PGE) was studied by Gangotri K.M. and Lal C. in the cell containing methylene blue and Azur B as Photosensitizers. The observed conversion efficiency was 0.1165% and the maximum output of the cell was 51.24 μW as power point.¹³ PGE was studied in photogalvanic cell containing ascorbic acid as reductant and eosin as photosensitizer. The conversion efficiency, maximum power and storage capacity of the cell were observed as 0.4474%, 46.5 μW and 36.0 min respectively.¹⁴ PGE was studied in photogalvanic cell containing nitrilotriacetic acid (NTA)-Azur B and sodium lauryl sulphate, cetyl pyridinium chloride and Tween 80 as surfactant for solar power generation. The conversion efficiency for anionic, cationic and nonionic surfactants above their CMC were 0.4053%, 0.1386% and 0.2177% and storage capacity 105, 31 and 74 min respectively.¹⁵ PGE was studied in dye sensitized cell containing EDTA and methylene blue and thionine. The observed conversion efficiency was 0.43% and the maximum output of cell was 67.68 μW . This cell can be used for 30 min in dark.¹⁶ Dye sensitized cell containing dioctylsulfosuccinate-mannitol-safranin system has been used for conversion of solar energy into electrical energy. The current voltage characteristics of the cell have been studied and conversion efficiency, fill factor and performance of the cell were observed as 0.7603%, 0.50 and 40.0 min respectively.¹⁷ PGE observed in Tween-80-EDTA-Safranin-O system. The conversion efficiency, fill factor and maximum power of the cell were observed 0.9769%, 0.34 and 235.50 μW respectively. The rate of initial generation of current was 80.0 $\mu\text{A min}^{-1}$ and this cell can be used for 60.0 minutes in the dark.¹⁸ A photosensitizer -Eosin and a reductant- Arabinose have been used by Gangotri K.M. and Bhimwal M.K. in the photogalvanic cell for photochemical conversion of solar energy into electrical energy. The conversion efficiency and the fill factor were observed 0.7026% and 0.2856 respectively at power point of the cell. This cell can work for 85.0 min in dark if it is irradiated for 140.0 min.¹⁹ A mixture of two reductants (Dextrose and EDTA) and Azur A used by Gangotri KM and Indora V. in the photogalvanic cell for solar power generation with aim to reduce the cost of construction for commercial viability. The power point of the cell, conversion efficiency and fill factor were observed 10.87 μW , 0.1045% and 0.1942 respectively.²⁰ The Brilliant Cresyl Blue and Fructose in alkaline medium have been studied for enhancing the solar energy conversion and storage capacity of the photogalvanic solar cell. In this study, the observed values of electrical parameters like maximum potential, maximum photocurrent, short-circuit current, power at power point, and conversion efficiency were 1115 mV, 785 μA , 590 μA , 183.3 μW , and 1.9586%, respectively.²¹ Safranin-NaLS-D Xylose system was used for enhancement of the electrical output and performance of the photogalvanic cell. The conversion efficiency and fill factor were observed 0.68% and 0.32 respectively at the power point of the cell.²² Rhodamine B and Fructose were used in alkaline medium to enhance the electrical output of the cell. The observed cell performance in terms of maximum potential, maximum photocurrent, short-circuit current, power at power point, conversion efficiency and storage capacity were 1071 mV, 1049 μA , 972 μA , 244.02 μW , 7.58% and 3.6 h, respectively.²³ Tergitol-7, EDTA and Azur-B chemicals used in a photogalvanic cell for solar energy conversion and storage. The observed values of the photogeneration of photopotential, photocurrent, conversion efficiency and fill factor are 778.0 mV, 45.0 μA , 0.14% and 0.3169 respectively. This cell can be used for 40.0 min in the dark.²⁴ The photogalvanic behaviour of Xylidine ponceau dye was studied in Xylidine ponceau-Tween 60-Ascorbic acid system. Cell generates maximum power of 68.77 μW in ideal conditions. Conversion efficiency was calculated by photopotential and photocurrent values at power point.²⁵ The Nile blue has been used as a photosensitizer with Arabinose in photogalvanic cell for optimum conversion efficiency and storage capacity. The conversion efficiency and fill factor were observed 0.6095% and 0.2566 respectively.²⁶ Solar energy conversion and storage was studied through Photogalvanic effect using photogalvanic cell containing Tween -80 as non-ionic surfactant with Toluidine Blue as photosensitizer and EDTA as reductant. The photopotential, photocurrent and storage capacity for this system were 430mV, 50 μA and 60 min. respectively. Conversion efficiency, fill factor, was also determined.²⁷

The scientific society has used various photosensitizers, surfactants, reductants in photogalvanic cells to convert solar energy into electrical energy, but no attention has been paid to the use of Chlorophenol Red dye as energy material

to increase the electrical output and performance of the photogalvanic cell. Therefore, present work has been done to obtain better performance and commercial viability of the photogalvanic cell.

Result and discussion

Effect of variation of Chlorophenol Red, isopropyl alcohol and NaLS concentration:

The effect of variation of Chlorophenol Red, isopropyl alcohol and NaLS concentration are given in Table 1. Variation of dye concentration studied by using solution of Chlorophenol Red of different concentrations. It was observed that the photopotential, photocurrent and power enhanced with enhancing in concentration of the dye [Chlorophenol Red]. A maximum (at 1150 mV, 735 μ A and 845.25 μ W) was obtained for a particular value of dye concentration (2.1×10^{-5} M), above which shortage in electrical output of the cell was observed. The low electrical output observed in the low concentration range of the dye due to the limited number of dye molecules to absorb most of the light in the path, while the high density of the dye also resulted in a decrease in output due to light intensity reaching the molecule near electrode decrease due to the absorption of a large portion of light by dye molecules present in the path, therefore corresponding fall in the electric output. With the increase in concentration of the reductant [isopropyl alcohol], the photopotential, photocurrent and power were found to increase till it reaches a maximum value at 1.8×10^{-3} M. These values are 1150 mV, 735 μ A and 845.25 μ W respectively. With further increase in isopropyl alcohol concentration, a decrease in the effect of cellular energy was observed. Decreased energy output also resulted in a reduction in reductant concentration due to the small number of molecules available to donate electrons to the cationic type of dye. On the other hand, the movement of dye molecules is prevented by the high concentration of reductant in order to reach the electrode at the desired time limit and will lead to a decrease in electrical output. The electrical output of the cell has been increased in increasing the concentration of surfactant [NaLS]. A maximum (1150 mV, 735 μ A and 845.25 μ W) result was obtained at a certain value (1.6×10^{-3} M) of concentration of NaLS. On further increasing the surfactant concentration it react as a barrier and major portion of the surfactant photobleach the less number of dye molecules so that a down fall in electrical output was observed.

Effect of variation of pH

Photogalvanic cell containing Chlorophenol Red - isopropyl alcohol -NaLS system was found to be very sensitive to the pH of the solution. It has been observed that there is an increase in photopotential, photocurrent and power with an increase in pH value (Alkaline range). At pH 10.40 a maxima was obtained (1150 mV, 735 μ A and 845.25 μ W). With an increase in pH, there was a decrease in photopotential, photocurrent and power. The optimum electrical output was obtained at particular pH value. It may be due to better availability of donor form of reductants at that pH value. The results showing the pH effect are summarized in Table 2.

Effect of diffusion length

The effect of variation of diffusion length (distance between two electrodes) on the current parameters of the cell (i_{max} , i_{eq} and initial rate of generation of photocurrent) was investigated using H-shaped cells of different dimensions. It was noted that in the first few minutes of illuminations there was sharp increase in photocurrent. As consequences, the maximum photocurrent (i_{max}) increase in diffusion length because path for photochemical reaction was increased, but this is not detected experimently. Whereas equilibrium photocurrent (i_{eq}) decreased linearly. Therefore, it may be concluded that the main electroactive species are the leuco or semi form of dye (photosensitizer) in the illuminated and dark chamber respectively. The results are summarized in Table 3.

The effect of electrode area on the current parameters of the cell was also studied. It was noted that with the increase in the electrode area the value of maximum photocurrent (i_{max}) is found to increase. Results are summarized in Table 4.

Effect of light intensity

The effect of light intensity was assessed using intensity meter (Solarimeter model-501). It was found that photocurrent showed a linear increasing behaviour with the increase in light intensity whereas photopotential increases in a logarithmic manner. The effect of variation of light intensity on the photopotential and photocurrent is graphically illustrated in Fig.1

Current-Voltage (i-V) characteristics of the cell

The short circuit current (i_{sc}) 735 μ A and open circuit voltage (V_{oc}) 1150 mV of the photogalvanic cell were measured with the help of a microammeter (keeping the circuit closed) and with a digital pH meter (keeping the circuit open), respectively. The current and potential values in between these two extreme values were recorded with the help of a carbon pot (log 470 K) connected in the circuit of multimeter, through which an external load was applied. The i-V characteristics of the photogalvanic cells containing Chlorophenol Red – isopropyl alcohol –NaLS system is graphically shown in Fig.2 and summarized in table 5. It was observed that i-V curve deviated from its regular rectangular shape. A point in the i-V curve, called power point (pp), was determined where the product of curve of current (i_{pp}) 389 μ A and

potential (V_{pp}) 599 mV was maximum. With the help of i-V curve, the fill-factor was calculated as 0.2756 using the formula:

$$\text{Fill factor } (\eta) = \frac{V_{pp} \times i_{pp}}{V_{oc} \times i_{sc}}$$

Cell performance and conversion efficiency

The performance of the photogalvanic cell was observed by applying an external load (necessary to have current at power point) after termination the illumination as soon as the potential reaches a constant value. The performance was determined in terms of $t_{1/2}$, i.e., the time required in fall of the output (power) to its half at power point in dark. It was observed that the cell containing Chlorophenol Red - isopropyl alcohol - NaLS can be used in dark for 165.0 minutes. With the help of current and potential values at power point and the incident power of radiations, the conversion efficiency of the cell was determined as 2.240 % using the formula. The results are graphically represented in time-power curve (Fig. 3).

$$\text{Conversion efficiency} = \frac{V_{pp} \times i_{pp}}{A \times 10.4 \text{ mWcm}^{-2}} \times 100\%$$

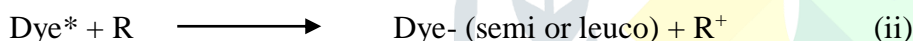
Mechanism

When certain dyes are excited by the light in the presence of electron donating substance (reductant), the dyes are rapidly changed into colourless form. The dye now acts as a powerful reducing agent and can donate electron to other substance and reconverted to its oxidized state. On the basis of earlier studies a tentative mechanism in the photogalvanic cell may be proposed as follows:

Illuminated chamber: On irradiation, dye molecules get excited.

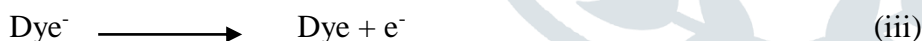


The excited dye molecules accept an electron from reductant and converted into semi or leuco form of dye, and the reductant into its excited form.



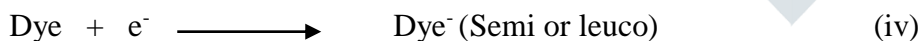
At platinum electrode:

The semi or leuco form of dye loses an electron and converted into original dye molecule.



Dark Chamber:

At counter electrode:



Finally leuco/semi form of dye and oxidized form of reductant combine to give original dye and reductant molecule. This cycle of mechanism is repeated again and again leading production of current continuously.



Here Dye, Dye^* , Dye^- , R and R^+ are the dye, its excited form, leuco form, reductant and its oxidized form, respectively. The scheme of mechanism is shown in Fig.4

Materials and methods

Chlorophenol Red (Ases Chemical, Jodhpur), isopropyl alcohol (Ases Chemical, Jodhpur), NaLS (Sisco Research Laboratories, Mumbai) and NaOH (RFCL, New Delhi) were used in the present work. Solutions of ascorbic acid, Chlorophenol Red, NaLS and NaOH (1N) were prepared in double distilled water (conductivity $3.5 \times 10^{-5} \text{ Sm}^{-1}$) and kept in amber coloured containers to protect them from sun light. Chlorophenol Red dye (Scheme 1) is an indicator dye that changes colour from yellow to violet in the pH range 4.8 to 6.7. The dye shows maximum absorption (λ_{max}) at 572 nm. A mixture of solutions of dye, reductant, surfactant and NaOH was taken in an H-type glass tube which was blackened by black carbon paper to unaffected from sun radiation. A shiny platinum foil electrode ($1.0 \times 1.0 \text{ cm}^2$) was immersed in one limb of the H-tube and a saturated calomel electrode (SCE) was immersed in the other limb. Platinum

electrode act as a working electrode and SCE as a counter electrode. The whole system was first placed in the dark till a stable potential was attained, then the limb containing the platinum electrode was exposed to a 200 W tungsten lamp (Philips). A water filter was used to cut off thermal radiation. Photochemical bleaching of the dye was studied potentiometrically. A digital multimeter (HAOYUE DT830D Digital Multimeter) was used to measure the potential and current generated by the system respectively. The current voltage characteristics were studied by applying an external load with the help of Carbon pot (log 470 K) connected in the circuit the photogalvanic cell set-up is shown in Figure 5.

Conclusions

India has a severe electricity shortage. It needs massive additions in capacity to meet the demand of its rapidly growing economy. Development of solar energy, which is indigenous and distributed and has low marginal cost of generation, can increase energy security by diversifying supply, reducing import dependence, and mitigating fuel price volatility. Solar energy development in India can also be an important tool for promoting regional economic development, particularly for many underdeveloped states, which have the greatest potential for developing solar power systems which is unlimited and clean source of energy. It can provide secure electricity supply to foster domestic industrial development. So it can be concluded that the photogalvanic cell have inbuilt storage capacity and stored energy can be used in absence of light, photogalvanic cells are favourable because low cost materials are used in these cells. The conversion efficiency, storage capacity, power at power point and fill factor are recorded as 2.240%, $t_{1/2}$ 165.0 min, 233.011 μW and 0.2756 respectively in Chlorophenol Red - isopropyl alcohol – NaLS system.

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Table -1. Effect of variation of Chlorophenol Red, isopropyl alcohol and NaLS concentrations			
Light Intensity = 10.4 mW cm ⁻² , Temperature = 303 K, pH = 10.40			
Concentrations	Photopotential (mV)	Photocurrent (μA)	Power (μW)
[Chlorophenol Red]$\times 10^{-5}\text{M}$			
1.5	625	500	312.50
1.7	950	564	535.80
2.1	1150	735	845.25
2.4	930	561	521.73
2.6	610	488	297.68
[isopropyl alcohol] $\times 10^{-3}\text{M}$			
1.4	855	578	494.48
1.6	1088	710	772.48
1.8	1150	735	845.25
2	1055	678	715.29
2.2	865	579	500.84
[NaLS] $\times 10^{-3}\text{M}$			
1.2	912	448	408.58
1.4	1079	630	679.77
1.6	1150	735	845.25
1.8	1077	708	762.52
2.0	923	478	441.19

Table –2 Effect of Variation of pH			
[Chlorophenol Red] = 2.1×10^{-5} M		Light Intensity = 10.4 mW cm^{-2}	
[isopropyl alcohol] = 1.8×10^{-3} M		Temperature = 303 K	
[NaLS] = 1.6×10^{-3} M			
pH	Photopotential (mV)	Photocurrent (μA)	Power (μW)
10.10	1167	515	601.01
10.20	1272	602	765.74
10.40	1440	735	1058.40
10.50	1260	628	791.28
10.60	1120	520	582.40

Table- 3 Effect of Diffusion Length and electrode area			
[Chlorophenol Red] = 2.1×10^{-5} M		Light Intensity = 10.4 mW cm^{-2}	
[isopropyl alcohol] = 1.8×10^{-3} M		Temperature = 303 K	
[NaLS] = 2.2×10^{-3} M		pH = 10.40	
Diffusion Length DL (mm)	Maximum Photocurrent i_{max} (μA)	Equilibrium Photocurrent i_{eq} (μA)	Rate of initial Generation of Current ($\mu\text{A min}^{-1}$)
35	823.0	748.0	21.66
40	834.0	744.0	21.95
45	845.0	735.0	22.24
50	850.0	730.0	22.37
55	852.0	722.0	22.42

Table - 4 Effect of Electrode Area		
[Chlorophenol Red] = 2.1×10^{-5} M		Light Intensity = 10.4 mW cm^{-2}
[isopropyl alcohol] = 1.8×10^{-3} M		Temperature = 303 K
[NaLS] = 1.6×10^{-3} M		pH = 10.40
Electrode Area (cm^2)	Maximum photocurrent i_{max} (μA)	Equilibrium photocurrent i_{eq} (μA)
0.70	810	757
0.85	825	745
1.00	845	735
1.15	860	729
1.30	875	722

Table-5 Current-Voltage (i-V) characteristics of the cell[Chlorophenol Red] = 2.1×10^{-5} MLight Intensity = 10.4 mW cm^{-2} [isopropyl alcohol] = 1.8×10^{-3} M

Temperature = 303 K

[NaLS] = 1.6×10^{-3} M

pH = 10.40

Potential (mV)	Photocurrent (μA)	Fill Factor (η)
1273	0	
1232	5	
1201	12	
1177	14	
1157	19	
1141	24	
1114	28	
1100	39	
1078	48	
1049	55	
1014	74	
977	91	
957	100	
938	104	
922	124	
900	130	
877	151	
854	164	
823	178	
791	199	
747	210	
717	224	
699	251	
698	288	
652	310	
647	330	
621	350	
600	370	
599	389	0.2756
523	413	
500	431	
455	489	
424	501	
414	502	
277	574	
224	604	
212	621	
100	700	
0	735	

Chlorophenol Red-Isopropyl alcohol-NaLS System

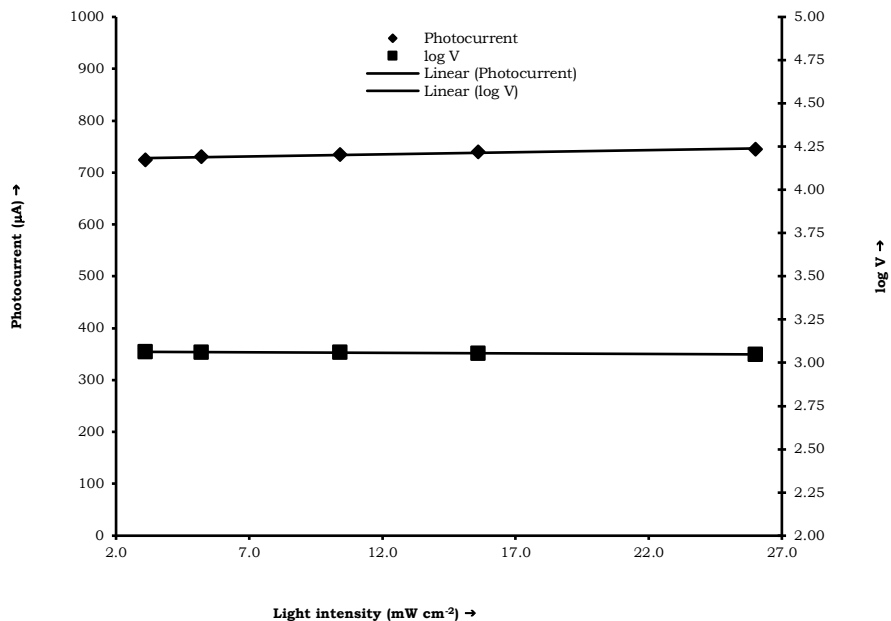


Fig. 1 VARIATION OF PHOTOCURRENT AND log V WITH LIGHT INTENSITY

Chlorophenol Red-Isopropyl alcohol-NaLS system

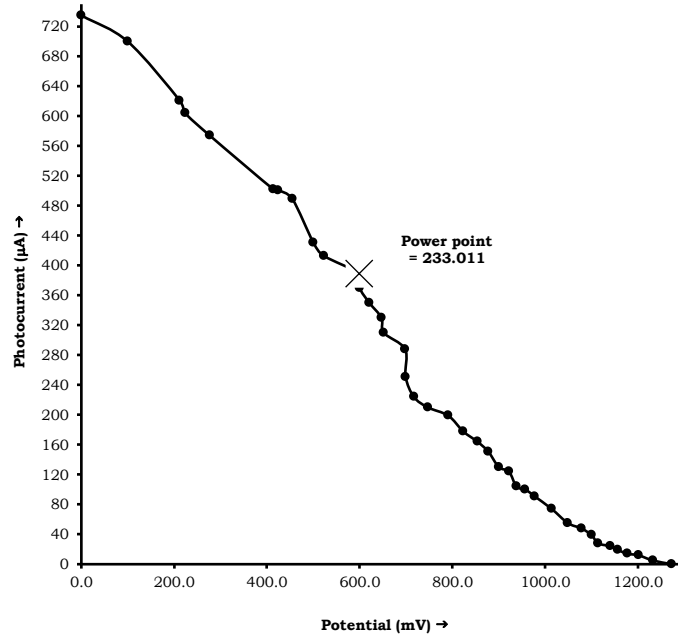


Fig. 2 CURRENT VOLTAGE (i-V) CURVE OF THE CELL

Chlorophenol Red - Isopropyl alcohol - NaLS

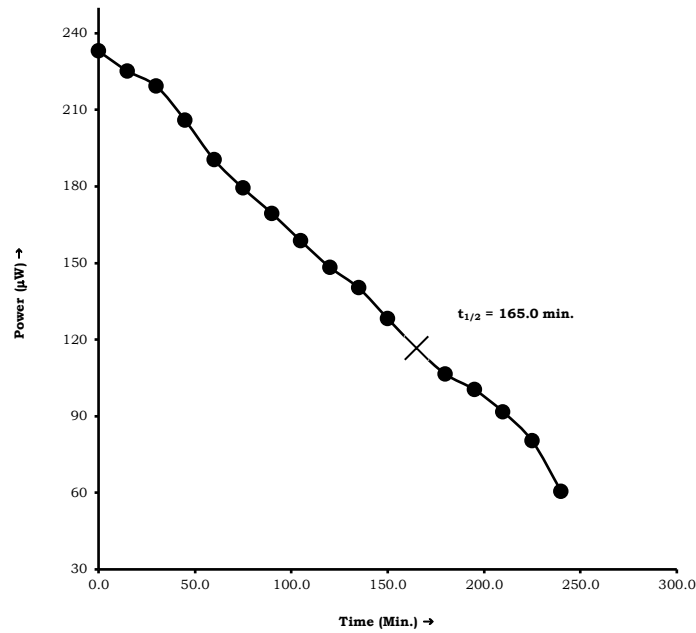


Fig. 3 TIME-POWER CURVE OF THE CELL

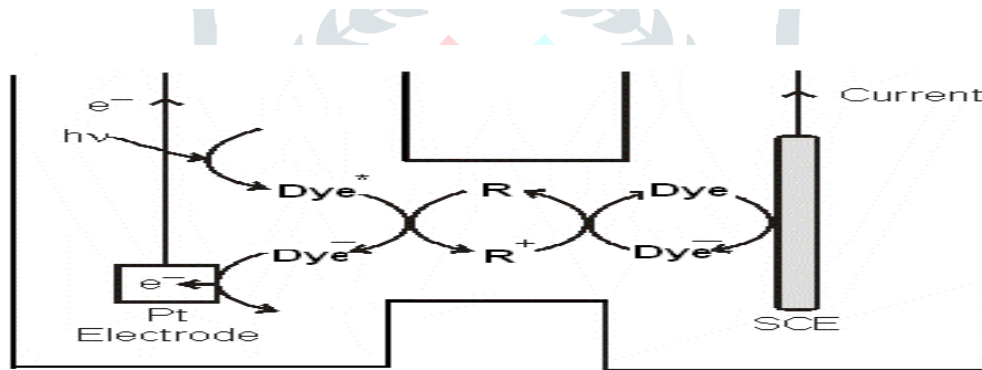
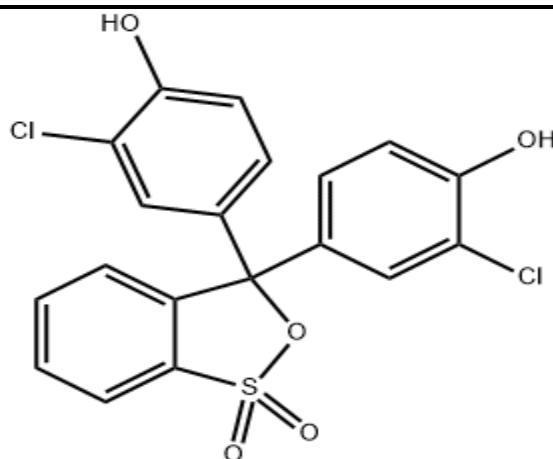


Fig. 4 Scheme of mechanism

SCE = Saturated calomel electrode
 R = Reductant

D = Dye (Photosensitizer)
 D = Semi & Leuco form



Scheme 4. Chlorophenol Red

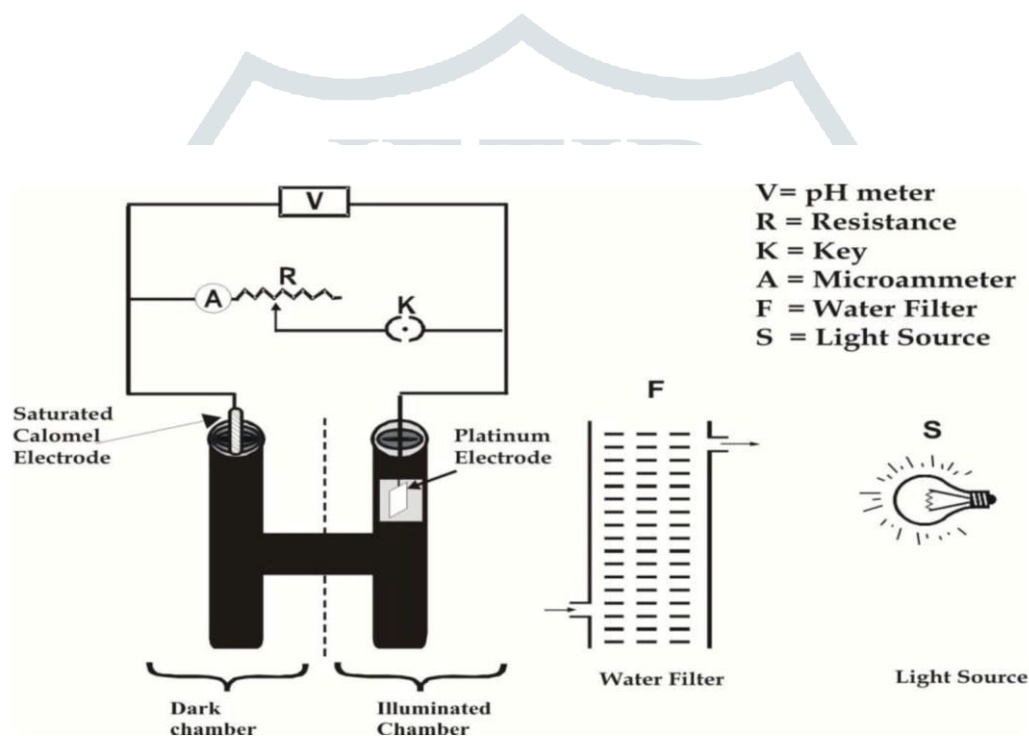


Fig.5 Photogalvanic Cell Set-up

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