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Operational Simulation of Solar-Powered Non-Asbestos Diaphragm Cells for the Production of Caustic Soda By Babatope Olufemi , Monisola Omotayo , Oluseyi Olawuwo , Oluwaseun Sese & Moradeyo Odunlami

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Keywords : Catholyte, diaphragm, energy, non-asbestos, simulation, solar.

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Operational Simulation of Solar-Powered Non-Asbestos Diaphragm Cells for the Production of Caustic Soda

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Abstract - Mathematical modeling and simulation of an experimental study was performed using an array of solar panels to power three non-asbestos diaphragm type electrochemical cells whose anodes consisted of carbon rods and cathodes made up of stainless steel plate for the electrolysis of a 25 % w/w sodium chloride solution, with the aim of producing caustic soda. The non-asbestos diaphragms served to hinder the formation of unwanted substances as well as permit reasonable production of the desired products. The three non-asbestos diaphragm cells exhibited various characteristic performances, which is a reflection of their design, fabrication, composition, intensity of the sun on any particular day, the length of time the panels were exposed to sunlight and operational parameters. The non-asbestos diaphragm D3 with composition of 60 % w/w Portland cement, 20 % w/w silica and 20 % w/w polyvinyl chloride (PVC) indicated the highest yield of caustic soda per d.c Watt with specific electrical energy supplied. The simulated values predicted the operation closely as the maximum positive and negative deviations of all modeled from experimental values are between +0.07 and -0.06 respectively. The research served as an encouraging inquisitive foundation into the possibility of producing caustic soda directly from solar powered electrolytic diaphragm cells with the aim of designing better cells as well as investigating key factors that affects cell performance in view of present conventional modes of electrochemical production.

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I. INTRODUCTION

he chlor-alkali (also called "chlorine-caustic") industry is one of the largest electrochemical technologies in the world. The electrochemical production of caustic soda from brine in the chlor-alkali industry, with chlorine and hydrogen as the by-products is one of the leading industrial production processes in the chemical industry. According to Alkire and Braatz (2004), electrochemical processes provide the only commercially viable means for the production of caustic soda, chlorine and some chemical products. Chlorine and/or caustic soda is involved directly or indirectly in the manufacture of about 70 percent of all chemical products (Ohm, 2007). The threat of inadequate electrical power has resulted in much effort toward reducing electrical power consumption.

chlor-alkali The process is the most economically important electrosynthetic process (Minteer, 2002). It is an energy intensive process and is the second largest consumer of electricity (2400 billion kWh) among electrolytic industries. In 2006, about 84 % of the total world chlorine capacity of about 59 million metric tons was produced electrolytically using diaphragm and membrane cells, while about 13 % was made using mercury cells (Tilak et. al, 2007). The diaphragm cell alone accounted for about 62% production (Tilak et. al, 2007).

According to Ohm (2007), a typical world-scale chloralkali-electrolysis plant produces above 1,000 tons of caustic soda a day. For this it consumes a shipload of salt (about 1,700 tons) and enough electricity to power a town in Germany with 130,000 inhabitants. Power consumption accounts for approximately 60 to 70 % of the total cost of industrial chlor-alkali production (Minteer, 2002; Patel, 2009). In addition, the power supply is highly unreliable, with frequent fluctuations, resulting in lower operational efficiency and higher input cost. Another inputs cost such as gas and petroleum fuel for running the captive power plant are rising steadily and do not show any signs of reduction in the near future. Cheap availability of gas is also a major concern.

Although the process chemistry of the chloralkali electrolytic production of caustic soda is simple to understand, the design and operational issues are vastly complex (Gunatillaka and Achwal, 2003). This particular area of production has witnessed, and is still witnessing drastic changes in the methods of production, all of which are directed towards achieving better ways of production in terms of yield, economics, operation, instrumentation, durability, environmental suitability and improvement on equipment design. Recently, low energy consumption in chlor-alkali cells using oxygen reduction electrodes was investigated by Kiros and Bursell (2008). A novel electrolytic cell which reduced power consumption by 91 % was recently developed with significantly superior kinetics, selectivity and efficiency compared to the traditional types of chloralkali cells for the production of caustic soda (Minteer,

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2002). The effect of magnetic field in chlor-alkali cells performance was also studied by Minteer and Burney (2005). Performance and durability enh ancement had been investigated for another chlor-alkali cell by Ichinose et *al.* (2004). Application of simulation results as well as relevant parameters and design criteria in the electrochemical industry for the operation of an Expanded Area Diaphragm Cell (EADC) for the electrochemical production of caustic soda with some results similar to what is obtainable in the industry had been carried out (Olufemi, 2008). Mathematical models which are abstract model that uses mathematical language to describe the behavior of a system are useful in electrochemical engineering.

In view of the above concerns, the chlor-alkali sector which is a basic driver of the economy has to play a pro-active role in optimizing energy efficiency and reducing wastage. Among the various strategies aimed to meet energy demand, efficient use of energy and its conservations emerges to be the least cost option in a global competitive environment. In energy conservation conscious countries, Energy Conservation Acts (ECAs) has specified the list of energy intensive industries and establishments as designated consumers. Chlor-alkali is one of such industries. Such consumers will have to carry out certain mandatory functions one of which is techno-economically implementing viable recommendations. The Chlor-Alkali industry has to aggressively pursue this agenda, not for meeting any lofty social obligation, but to ensure its own survival and growth. Members of the Chlor-alkali industry can adopt several such strategies. Reduced energy-consuming chlor-alkali process through solar power derived energy is a good recommendation for the process.

This work is set-out to study and put forward successful implementation of techno-economically viable recommendations in the chlor-alkali industry. The possibility of this is to be explored by theoretical investigation and experimental demonstration of the usage of solar powered electrolytic non-asbestos diaphragm cells for the production of caustic soda, with consideration for their performance and operational characteristics.

II. EXPERIMENTAL

The experimental set up consisted of electrochemical cells with anolyte and catholyte compartments, graphite anodes, stainless steel cathodes, array of solar panels producing electric current, a voltmeter, an ammeter, a charge controller and ducts used to collect products of electrolysis. Additional apparatus employed in the preparation of 25 % w/w brine and 2.78 M HCl for titration were; volumetric flask, a measuring cylinder, an electronic weighing balance, a stirrer, distilled water and crystalline sodium chloride. Apparatus involved in the titration were beakers, retort, burette, conical flask, and pipette. A total

of 6 hours electrolysis time was taken for each daily run, with the open and closed cell voltages and current taken at hourly intervals for three days a week. Inlet temperature of brine was 313 K for all runs, while the final is about 315 K for all runs. Non-asbestos plates with compositions given in Table 1, were separately prepared, and were subsequently adhered to the cathode plates, for use as diaphragms. The schematic electrochemical operational diagram for all the cells is shown in Figure 1.

Material	Diaphragm D1	Diaphragm D2	Diaphragm D3
Silica	10%	15%	20%
PVC	10%	15%	20%
Cement	80%	70%	60%

Table 1 : Weight percent of non-asbestos diaphragms

Solar modules were firmly fixed in place, in a manner suitable to withstand all expected loads. The modules were mounted with the orientation and tilt angle required for optimum performance. Its location was selected to have direct access to sunlight from 0900 to 1500 hours GMT. The tilt angle was maintained at 20 degrees to the horizontal, with modules facing south in the northern hemisphere or north in the southern hemisphere as the case may be. During installation of the modules, so as to avoid the destruction of the solar cells, bypass diodes and junction box, the correct polarity was observed and blocking diodes were used to prevent reversal flow of current to the panels. Positive wires from modules were connected to the positive terminal of the charge controller and negative wires from the modules were connected to the negative terminal of the charge controller. Positive wires from the charge controller were connected to the cell anodes and negative wires from the charge controller were connected to the cell cathodes. Insulated copper wires were used to connect the panels in parallel to the charge controller and cells.

The voltage supplies from the panels were suitable to drive the electrochemical reaction and circuit resistances. The theoretical overcome decomposition voltage needed is 2.3 V. The parallel array of the solar panels used has an average open circuit voltage of about 18.4 V. The open circuit voltage was taken at the beginning of each run on a daily basis, and each cell was operated for three days a week for a total of five weeks. The products generated were chlorine gas, hydrogen gas and caustic soda solution. It was observed that after the second day of operation, a sizeable quantity of liquor had been produced and consistent production followed thereafter. Electrolytic product was consequently withdrawn from the cathodic end of the electrolytic cell.







III. MATHEMATICAL MODEL DEVELOPMENT

The overall electrically-driven reaction within the cells is given as:

$$2NaCl(aq) + 2H_2O(l) \longrightarrow 2NaOH(aq) + H_2(g) + Cl_2(g)$$





ν

The arrangement of the anode, anolyte height, diaphragm and cathode with the direct current (d.c) source for the cells are shown in Figure 2.

The total cell voltage V must be high enough to drive the electrochemical reaction despite all circuit resistances. Since a dry diaphragm is non-conducting, the performance of the cell depends on the hydrodynamic flow process through the wet porous diaphragm. Fluid flow in porous media is very similar to fluid flow in packed beds, due to the similarity of the flow channels through which fluid passes (Seader and Ernest, 1998). If A_D is the total surface area of the diaphragm normal to the direction of fluid flow, the average velocity across the cross-sectional area of the diaphragm is given as:

$$F_{D,ave} = \frac{\int_{0}^{A_{D}} v_{ave} dA_{D}}{\int_{0}^{A_{D}} dA_{D}} = \frac{\pi D_{P}^{2} \varepsilon^{3} (P_{O} - P_{L})}{144(1 - \varepsilon)^{2} \pi d_{D} \mu} \quad (2)$$

(1)

 \Rightarrow

and the volumetric flow rate of fluid across the diaphragm surface is given as:

$$\dot{V}_{\rm D} = \frac{A_{\rm D} . \pi D_{\rm P}^{\ 2} \varepsilon^{3} (P_{\rm O} - P_{\rm L})}{144(1 - \varepsilon)^{2} \tau l_{\rm D} \mu}$$
(3)

If Λ is the equivalent conductance of the flowing electrolyte through the diaphragm, the dynamic resistance of the diaphragm is given as:

$$R_{\rm D} = \frac{\pi D_{\rm P}^{2} \varepsilon^{3} (P_{\rm O} - P_{\rm L})}{144\Lambda (1 - \varepsilon)^{2} \tau \mu} \tag{4}$$

 $V = 2.3 - \eta_{A} + \eta_{C} + \frac{\pi D_{P}^{2} \varepsilon^{3} (P_{O} - P_{L}) l_{S} I_{MD}}{144 \Lambda (1 - \varepsilon)^{2} \tau l_{D} \mu} + \frac{\pi D_{P}^{2} \varepsilon^{3} (P_{O} - P_{L}) I_{MD}}{144 \Lambda (1 - \varepsilon)^{2} \tau \mu} + I_{MD} R_{m}$ (6)

Rearranging Equation (6) and solving for the average current, ${\rm I}_{\rm MD}$

$$I_{MD} = \frac{V - 2.3 + \eta_A - \eta_C}{\left[\frac{\pi D_P^2 \varepsilon^3 (P_O - P_L)}{144\Lambda (1 - \varepsilon)^2 \tau \mu} \left(\frac{l_s}{l_D} + 1\right) + R_m\right]}$$
(7)

The average electrical power required by the cell is given as:

$$P_{\rm MD} = \frac{V^2 - 2.3V + \eta_{\rm A}V - \eta_{\rm C}V}{\left[\frac{\pi D_{\rm P}^2 \epsilon^3 (P_{\rm O} - P_{\rm L})}{144\Lambda (1 - \epsilon)^2 \tau \mu} \left(\frac{1_{\rm s}}{l_{\rm D}} + 1\right) + R_{\rm m}\right]}$$
(8)

Equation (7) gives the value of the modelled current (I_{MD}) in Amperes, and Equation (8) gives the power requirement of the cell at any time.

The rate of formation of NaOH depends on the influx of Na⁺ ions passing through the diaphragm from the anode to the cathode compartment. Due to the similarity of flow channels in the diaphragms, according to Olufemi et *al.* (2000) and Olufemi (2008), the Geometrically Dependent Operational Current Effectiveness (GDOCE) based on cell design geometry and operating condition can be utilized in modeling the cells productivity. The GDOCE is defined as the ratio of the minimum current density required to convert completely the influx of the electrolyte, to the minimum current density furnished by either electrode.

$$\eta_{MD} = \frac{I_{MN} / A_{EL}}{I_{MD} / A_{AC}} \tag{9}$$

If $\eta_{\scriptscriptstyle MD} \leq 1$, then

Also, the dynamic resistance of the electrolyte as it flows through the cell is:

$$R_{S} = \frac{\pi D_{p}^{2} \varepsilon^{3} (P_{O} - P_{L}) l_{S}}{144\Lambda (1 - \varepsilon)^{2} \tau l_{D} \mu}$$
(5)

If the anode overvoltage is η_a , the cathode overvoltage is η_c , the dynamic resistance of the other miscellaneous components in the circuit is R_m , the average modelled current is I_{MD} , then

$$(I_{MN} / A_{EL}) \le (I_{MD} / A_{AC})$$
(10)

If $\eta_{MD} \ge 1$, it means that the efficiency of the cell is not geometrically dependent, and could only be determined through other means. The minimum current required to produce 100 percent of the desired product through the complete conversion of the influx of the electrolyte feed can be obtained as follow:

$$I_{MN} = \frac{N_A z w \rho_{EL} \dot{V}_D}{e_{WF}} \tag{11}$$

 A_{EL} is the most geometrically uniform electroactive surface area of the separator for either side of the two half-cells. A_{AC} represents the electroactive surface area of the electrode that has the most geometrically uniform electroactive surface area per unit volume of effective inventory of electrolyte within the reactor (Pletcher and Walsh, 1990).

Thus for the anode,

$$A_{IA} = \frac{A_A}{\dot{V}_D} \tag{12}$$

For the cathode,

$$A_{IC} = \frac{A_C}{\dot{V}_D} \tag{13}$$

The particular electroactive surface area of the electrode that gives the highest value between A_{IA} and $A_{IC},$ gives the value of the A_{AC} to be used for the determination of the GDOCE.

From the foregoing based on Faradays laws of electrolysis, the maximum electrolytic yield of caustic soda within the cell per unit time is given as:

$$\dot{m}_{HS} = \frac{I_{MD} e_{WS}}{N_A z} = \frac{(V - 2.3 + \eta_A - \eta_C) e_{WS}}{\left[\frac{\pi D_P^2 \varepsilon^3 (P_O - P_L)}{144\Lambda (1 - \varepsilon)^2 \tau \mu} \left(\frac{l_s}{l_D} + 1\right) + R_m\right] N_A z}$$
(14)

where,

 $N_A = 6.02205 \text{ X } 10^{26} \text{ kmol}^{-1}, z = 1.60219 \text{ X } 10^{-19} \text{ C},$ $e_{WS} = 40 \text{ kgkmol}^{-1}, e_{WE} = 58.5 \text{ kgkmol}^{-1}$ By introducing the GDOCE, which gives the constructive portion of the current density available for the desired reaction, the modelled electrolytic yield of caustic soda within the cell per unit time is given as:

$$\dot{m}_{MS} = \frac{I_{MD}\eta_{MD}e_{WS}}{N_{A}z} = \frac{(V - 2.3 + \eta_{A} - \eta_{C})\eta_{MD}e_{WS}}{\left[\frac{\pi D_{P}^{2}\varepsilon^{3}(P_{O} - P_{L})}{144\Lambda(1 - \varepsilon)^{2}\tau\mu}\left(\frac{l_{s}}{l_{D}} + 1\right) + R_{m}\right]N_{A}z}$$
(15)

Thus in the limit as every other sources of inefficiency (side reactions, physical loss of products outside the cell, measurement errors, effect of the separating medium) tends to zero, the modelled current efficiency obtained from the modelled volumetric flow rate, current and the GDOCE can also be expressed as:

$$\eta_{MD} = \frac{\dot{m}_{MS}}{\dot{m}_{HS}} \tag{16}$$

The observed operational current efficiency could be obtained from the theoretical production rate expected from the observed operational current (I_{OB}), and the observed production rate of caustic soda(\dot{m}_{OS}). The theoretical production rate expected from the observed operational current is given as:

$$\dot{m}_{TH} = \frac{I_{OB} e_{WS}}{F} \tag{17}$$

Therefore the observed operational current efficiency is given as:

$$\eta_{OB} = \frac{\dot{m}_{OS}}{\dot{m}_{TH}} = \frac{C_{OS}\dot{V}_{OB}F}{I_{OB}e_{WS}}$$
(18)

The observed production rate of caustic soda is given as:

$$\dot{m}_{OS} = C_{OS} \dot{V}_{OB} \tag{19}$$

Therefore the observed operational current efficiency is given as:

$$\eta_{OB} = \frac{\dot{m}_{OS}}{\dot{m}_{TH}} = \frac{C_{OS}\dot{V}_{OB}F}{I_{OB}e_{WS}}$$
(20)

$$Molarity = \frac{C_{OS}}{40}$$
(21)

Experimental specific electrical energy =
$$\frac{P_{OB}}{\dot{m}_{OS}}$$
 (22)

Modelled specific electrical energy =
$$\frac{P_{MD}}{\dot{m}_{MS}}$$
 (23)

Yield =
$$\frac{\dot{m}_{OS}}{\text{inlet mass flow rate of brine feed}}$$

Yield /d.c Watt =
$$\frac{Yield}{P_{MD}}$$
 (25)

The deviation (ΔE_{x}) of modelled value ($X_{_{MD}}$) from corresponding experimental value ($X_{_{EXP}}$) is given as:

$$\Delta E_{x} = \frac{X_{MD} - X_{EXP}}{X_{EXP}}$$
(26)

IV. RESULTS AND DISCUSSION

It was observed for all operations that the open circuit voltage was always greater than the cell voltage at loading. This was because of the fact that loading caused a drop in potential, in addition to the effect of the charge controller on the cells also. The charge controller was needed to regulate the amount of current entering into the cell, and also to prevent the backward flow of electricity from the cell to the solar panels as a result of the electrochemical potential generated in the cell by reason of the electrochemical reactions. Furthermore, it was observed that the amount of electricity generated by the solar panels varied with the intensity of the sun on each particular day. The highest voltage was observed for the hottest day and vice-versa. The values of current, mass flow rate, efficiency and so on obtained for the

(24)

three cells closely resemble the range obtained for diaphragm cells operated by stepped down a.c to d.c rectified power supply from mains and solar powered cells (Olufemi et al, 1999, 2000, 2008, 2011). The applicable simulated values were estimated at their corresponding experimental counterparts as presented from Equations 1 to 26. The simulated values were estimated algebraically from the appropriate relationships and validated with their corresponding The variation of average current experimental values. with average voltage for all the non-asbestos diaphragm cells is shown in Figure 3. Higher currents with corresponding voltages were observed for the diaphragm cells as the weight percent of the cement reduces, while those of silica and PVC increases. The cells confirmed the ohmic direct proportional relationship that current increases linearly with voltage. The non-asbestos cell with diaphragm D1 seems to have a higher operational electrical resistance with respect to the present operation. The simulated values matched the experimental values closely.

In Figure 4, the molar concentration of caustic soda in the catholyte products of the three cells is shown to increase with average cell current. The cell with non-asbestos diaphragm D1 produced more concentrated solutions relatively than the others with respect to the present electrochemical operation. Despite the fact that the cell with Diaphragm D1 operated at a higher electrical current than its counterparts at corresponding voltages, it still produced more concentrated products. The cell with diaphragm D1 seems to be better in the production of more concentrated product in this regard. The reason may be due to the fact that the diaphragm is less permeable than the others resulting in relatively higher residence time of the reacting species at the electrodes. This means that conversion will be higher per unit space volume of cell. The modeled values seem to closely match the experimental counterparts for all the diaphragm cells.



Figure 3 : Variation of current with voltage for the nonasbestos diaphragm cells



Figure 4 : Variation of concentration with current for the non-asbestos diaphragm cells

Variation of the mass flow rate of caustic soda produced for the two cells with average operational current is plotted in Figure 5. As expected from the previous plot, diaphragm D3 electrochemical cell resulted in higher mass flow rate than the other cells. This follows directly from the fact that this diaphragm is more permeable in the present operation. However it can be observed in the three cells that the mass flow rate increased to a maximum value and then declined. This means that operation at too high current values can lead to energy wastage if not controlled. This is a subject of optimum cell design and optimum cell operation. The simulated values matched the experimental values perfectly with the deviation less than $\pm 6\%$.

The variation of average current efficiency with operational voltage is shown in Figure 6. As it can be deducted from the operation of the cells, too high voltage above the theoretical decomposition voltage leads to reduction in efficiency, thereby resulting in more energy wastage. The diaphragm D3 cell recorded the highest current efficiencies with respect to the present operational procedure. The relatively higher permeable nature and relatively lower operating voltage of the diaphragm may be responsible for its higher current efficiency relative to other counterparts. As depicted also, the simulation closely predicts the experimental values.

The yield (kg NaOH / kg NaCl input) increased with voltage in Figure 7, with that of the non-asbestos diaphragm D3 cell indicating higher yield with respect to operational voltages recorded. This showed the possibility of improving the yield of caustic soda produced with increased operational voltages for the cells. The simulated values seem to match the experimental values perfectly.



Figure 5 : Variation of mass flow rate with current for the non-asbestos diaphragm cells



Figure 6 : Variation of current efficiency with operational voltage for the non-asbestos diaphragm cells



Figure 7 : Variation of yield with operational voltage for the non-asbestos diaphragm cells

In Figure 8, the non-asbestos diaphragm D3 cell showed a better yield per d.c Watt than the other cells. This indicated that the cell in the present operation produced more desired product than the other cells at corresponding electrical d.c power supplied. The yield / d.c Watt is a good indication of the electrical power effectiveness of substance producing electrochemical cells. The maximum positive and negative deviations of simulated from experimental data was between +0.06 and -0.05 respectively.



Figure 8 : Variation of yield with yield/d.c Watt for the asbestos and non-asbestos diaphragm cells

In Figure 9, the variation of the yield with specific electrical energy for the production of caustic soda is shown. It can be deduced that the yield increases with the specific electrical energy needed to produce 1 kg of caustic soda the three cells. From the plot, the yield seems higher with the specific energy required by the non-asbestos diaphragm D3 cell in comparison with other cells. This is a strong indication that if improved upon, these non-asbestos diaphragm cells have a higher capability of producing more caustic soda for the same electrical energy supplied. In comparison with industrial cells, the specific energy required by commercial diaphragm cells approximately varies from 1.38 x 10^7 to 2.03 x 10^7 J / kg, with current densities ranging between 900 to 2600 A / m² (Worell et al, 2000; Tilak et al, 2007). The three laboratory scale cells presented here required higher specific energy per kilogram of caustic soda produced in the present operation. The current densities employed in the solar powered cells ranged from 55.21 to 160.42 A / m², which is relatively lower to commercial diaphragm cells current densities. This is likely to be the reason for the relatively higher specific energy required per kilogram of caustic soda produced. Appropriate scale-up and optimization techniques of the solar powered cells could make the values comparable. The simulation seems to closely predict the experimental values.





v. Conclusion

From the results obtained, the modeling and simulation presented in this work closely predicted the cell operations, as the maximum positive and negative deviations of simulated from experimental data was between +0.07 and -0.06 respectively. From the results obtained from the cell operations, it can be reasonably concluded that the non-asbestos diaphragm D3 cell seems to be more preferred, because its yield and productivity is comparatively better to that of other non-asbestos diaphragm cells. This reflects its higher permeability due to the lower percentage of Portland cement and higher percentages of PVC and silica relative to others.

As observed, a solar powered diaphragm cell is capable of producing caustic soda of specification closely equal to those produced by conventionally powered diaphragm cells of similar scale, as long as the solar panels are capable of generating enough voltage to overcome cell and circuit resistance by situating it in an appropriate location, installing them correctly, and completing the circuit as required. The advantages of the present work are that the cells can be operated without the use of conventional electric power, since the only energy required comes directly from the sun. Also the operation can be a very compact process that fits into a small area or can be scaled up to the required size depending on the capacity of production. The process promised to be very economical and very flexible in terms of expansion. The operation is environmentally friendly, because the only form of energy required is solar. The disadvantages of the operation are that it is not highly efficient after sunset and during rainfall. Also, production is not constant but depends on the sun's intensity.

With further research on appropriate scale-up and optimization techniques, solar powered cells could possibly match commercial scale conventional cells in certain performances. The maximum current density employed was 160.42 A / m^2 for the three cells combined together. This is low compared with those employed in conventional commercial diaphragm cells which in many cases range from 900 to 2600 A / m^2 (Worell et al, 2000; Tilak et al, 2007). However, a very important factor which the solar powered cells are expected to achieve is to have a high output of material for little input of material and energy, which is the recent trend in the chlor-alkali industry, according to Minteer (2002) and Sugiyama et *al.* (2003).

Above all, this direct solar energy powered means of producing caustic soda with electrochemical cells could be a very commercially viable project in areas where the power situation is epileptic, erratic and undergoing reforms, considering the fact that those areas might need to have abundant sunlight for better part of the year.

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Symbols

 A_A , A_{AC} , A_C , A_D , A_{EL} , A_{IA} , A_{IC} = Area (m²)

 C_{OS} = Observed caustic soda concentration (kg/m³) D_{P} = Pore Diameter (m)

 e_{WS} , e_{WE} = Equivalent weight (kg/kgmol)

- F = Faraday's Constant (C/mol)
- g = Acceleration due to gravity (m/s²)
- $h_t = \text{Height of anolyte (m)}$
- $I_{\text{MD}},\,I_{\text{OB}},\,I_{\text{MN}}=\,\text{Current}\;(\text{A})$
- $l_{\rm D} = {\rm Diaphragm \ thickness \ (m)}$
- l_s = Distance between electrodes (m)
- \mathbf{k} = Average electrolyte specific conductivity (Ohm⁻¹m⁻¹)
- m = lonic mobility of hydroxyl ion (m/s)(V/m)

\dot{m}_{OS} , \dot{m}_{OB} , \dot{m}_{HS} , \dot{m}_{MS} = Mass flow rate (kg/s)

- $N_A = Avogadro's$ number
- P_{O} , P_{L} = Pressure (N/m²)
- P_{MD} = Modelled Power (Watt)
- $R_m = Resistance (Ohm)$
- r_{RA}, r_{RC} = Reaction rate (mol/m²s)
- T = Temperature (K)
- t = time (s)
- $v, V = Volume (m^3), Voltage (V)$

- \dot{V}_D , \dot{V}_{OB} = Volumetric flow rate (m³/s)
- w = Percentage weight
- z = Electron Charge (C)

GREEK ALPHABET

- ρ_{EL} = Density of electrolyte(kg/m³)
- $\tau = Tortuosity factor$
- \mathcal{E} = Porosity
- Λ = Equivalent Conductance (Ohm⁻¹ m²)
- $\eta ~=~ \text{Overvoltage (V)}$

$$\eta_{\scriptscriptstyle MD}$$
 , $\eta_{\scriptscriptstyle OB}$ = Current efficiency

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