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Operational Simulation of Solar-Powered Variant-Diaphragm Cells for Caustic Soda Production

Babatope Olufemi*, Williams Ozowe and Kazeem Afolabi
Department of Chemical Engineering, University of Lagos, Akoka, Lagos, Nigeria
*E-mail of the corresponding author: bolufemi@yahoo.com

Abstract

The application of mathematical models for the operational simulation of asbestos and non-asbestos diaphragm-type electrolytic cells, powered by an array of solar panels was carried out. Carbon rods and stainless steel plates were used as the anode and cathode respectively for the electrolysis of 25% w/w sodium chloride solution. With the aid of the asbestos and non-asbestos diaphragms which served to hinder the formation of unwanted substances as well as permit reasonable production of the desired products, caustic soda, chlorine and hydrogen were produced. As observed, the asbestos and non-asbestos diaphragm cells exhibited various characteristic performances, which is a reflection of their design, fabrication, composition and operational parameters. From the investigation, the non-asbestos diaphragm cell showed similar trend with the conventional asbestos diaphragm cell type, with performances that indicated higher yield of caustic soda per d.c Watt. The simulated values closely represented the experimental operation with the maximum positive and negative deviations of all modeled from experimental values are between +0.08 and -0.06 respectively. The aim of the research is to serve as an encouraging inquisitive foundation into the possibility of producing caustic soda directly from solar powered electrolytic diaphragm cells, with the possibility of designing better cells in future.

Keywords: caustic soda, simulation, asbestos, diaphragm cells, solar, non-asbestos, energy.

1. Introduction

It is an established fact that the electrochemical production of caustic soda from brine in the chlor-alkali industry, with chlorine and hydrogen as the by-products is among 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. The chlor-alkali process is the most economically important electrosynthetic process (Minteer, 2002). The chlor-alkali (also called "chlorine-caustic") industry is one of the largest electrochemical technologies in the world. 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. The threat of inadequate electrical power has resulted in much effort toward reducing electrical power consumption. Power consumption accounts for approximately 60 to 70% of the total cost of industrial chlor-alkali production (Minteer, 2002; Patel, 2009). From the accounts of Patel (2009), power supply is highly unreliable, with frequent fluctuations, resulting in lower operational efficiency and higher input cost, especially the costs of gas and petroleum fuel.

Although the process chemistry of the chlor-alkali 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 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, targeted towards optimization. Low energy consumption in chlor-alkali cells using oxygen reduction electrodes had been investigated by Kiros and Bursell (2008). A novel electrolytic cell which reduced power consumption by 91% had also been developed with significantly superior kinetics, selectivity and efficiency compared to the traditional types of chlor-alkali cells for the production of caustic soda (Minteer, 2002). The effect of magnetic field in chlor-alkali cells performance was also studied by Minteer and Burney (2005). Performance and durability enhancement was 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 et *al.*, 2010).

In some observations by Patel (2009), 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, while efficient use of energy and its conservations was identified to be the least cost option. As stated also by Patel (2009), Energy Conservation Acts (ECAs) in some countries had specified the list of energy intensive industries and establishments as designated consumers, in which Chlor-alkali is one of such industry, where such designated consumers will have to carry out certain mandatory functions in which one of them is to implement techno-economically viable recommendations and submit to the designated authority periodic reports on steps taken by them. The chlor-Alkali industry has to aggressively pursue the energy conservation agenda - not so much for meeting any lofty social obligation, but to ensure its own survival and growth (Patel, 2009). Reduced energy-consuming chlor-alkali process with solar derived energy seems to be a good recommendation for the process as will be explored in this work.

Purposely, this work is 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 based on experimental demonstration of the usage of solar powered electrolytic asbestos and non-asbestos diaphragm cells for the production of caustic soda.

2. Experimental Operation

Figure 1 presented the 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 2.78M 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 313K for all runs, while the final is about 315K for all runs. Asbestos plate (85% cement and 15% chrysolite asbestos) and non-asbestos plate (85% cement, 7.5% PVC and 7.5% Silica), were separately prepared, and were subsequently adhered to the cathode plate, for use as diaphragms to aid the comparative study.

The solar modules were tightly 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 being in the northern hemisphere. 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 wire from modules was connected to the positive terminal of the charge controller and negative wire from the modules was connected to the negative terminal of the charge controller. Positive wire from the charge controller was connected to the cell anode and negative wire from the charge controller was connected to the cell cathode. Insulated copper wire was used to connect the panels in parallel to the charge controller and cells. The charge controller was used 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. The highest voltage was observed for the hottest day and vice-versa.

The voltage supply from the panels was suitable to drive the electrochemical reaction and overcome circuit resistances. The theoretical decomposition voltage needed is 2.3V. The parallel array of the solar panels used has an average open circuit voltage of about 18.4V. 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 withdrawn from the cathodic end of the electrolytic cell.

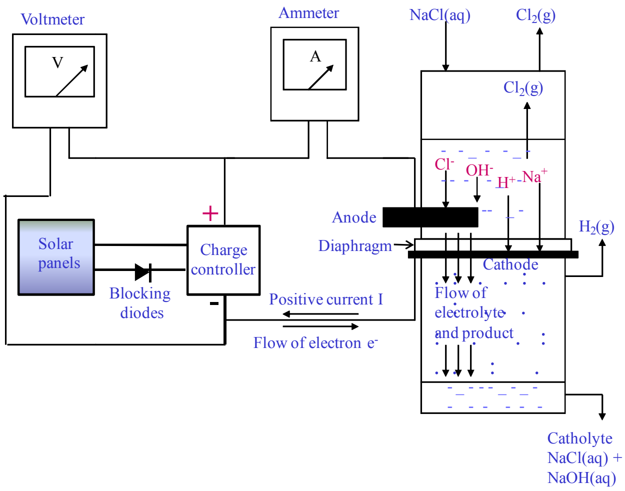

Figure 1: Schematic electrochemical operational diagram of solar powered diaphragm cells (Olufemi et *al.*, 2011, 2012).

3. Mathematical Model Description

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

$$2NaCl(aq) + 2H_2O(l) \longrightarrow 2NaOH(aq) + H_2(g) + Cl_2(g) \quad (1)$$

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.

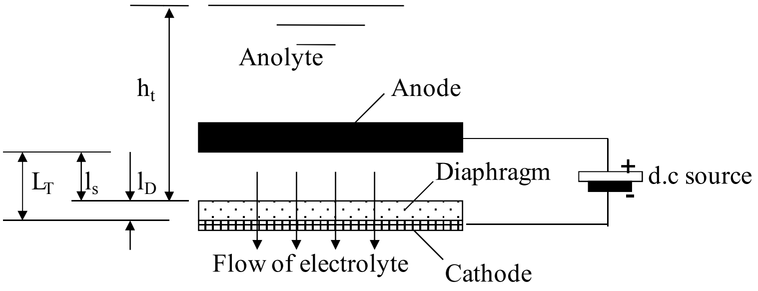

Figure 2: Spatial arrangement of the anode, diaphragm and cathode

The adopted model description for the cells is similar to those of some diaphragm cells reported in the literature (Olufemi et al., 2010, 2012). For smooth operation, 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:

$$v_{D,ave} = \frac{\int_0^{A_D} v_{ave} dA_D}{\int_0^{A_D} dA_D} = \frac{\pi D_P{}^2 \varepsilon^3 (P_O - P_L)}{144(1-\varepsilon)^2 \tau l_D \mu} \quad (2)$$

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

$$\dot{V}_D = \frac{A_D . \pi D_P{}^2 \varepsilon^3 (P_O - P_L)}{144(1-\varepsilon)^2 \tau l_D \mu} \quad (3)$$

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

$$R_D = \frac{\pi D_P{}^2 \varepsilon^3 (P_O - P_L)}{144\Lambda(1-\varepsilon)^2 \tau\mu} \tag{4}$$

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

$$R_S = \frac{\pi D_p^2 \varepsilon^3 (P_O - P_L) l_S}{144\Lambda(1-\varepsilon)^2 \tau l_D \mu} \tag{5}$$

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

$$V = 2.3 - \eta_A + \eta_C + \frac{\pi D_P{}^2 \varepsilon^3 (P_O - P_L) l_S I_{MD}}{144\Lambda(1-\varepsilon)^2 \tau l_D \mu} + \frac{\pi D_P{}^2 \varepsilon^3 (P_O - P_L) I_{MD}}{144\Lambda(1-\varepsilon)^2 \tau\mu} + I_{MD} R_m \tag{6}$$

Rearranging Equation (6) and solving for the average current, I_{MD}

$\Rightarrow$

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

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

$$P_{MD} = \frac{V^2 - 2.3V + \eta_A V - \eta_C V}{\left[\frac{\pi D_P^2 \varepsilon^3 (P_O - P_L)}{144\Lambda(1-\varepsilon)^2 \tau\mu}\left(\frac{l_s}{l_D} + 1\right) + R_m\right]} \tag{8}$$

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, 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 (Olufemi et *al.*, 2010, 2012).

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

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

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

If $\eta_{MD} \geq 1$, 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:

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

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:

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

where,

$N_A = 6.02205 \text{ X } 10^{26}$ kmol^{-1}, $z = 1.60219 \text{ X } 10^{-19}$ C, e_{WS} = 40 kgkmol^{-1}, e_{WE} = 58.5 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:

$$\dot{m}_{MS} = \frac{I_{MD} \eta_{MD} e_{WS}}{N_A z} = \frac{(V - 2.3 + \eta_A - \eta_C) \eta_{MD} e_{WS}}{\left[\frac{\pi D_P^2 \varepsilon^3 (P_O - P_L)}{144 \Lambda (1-\varepsilon)^2 \tau \mu} \left(\frac{l_s}{l_D} + 1 \right) + R_m \right] N_A z} \tag{15}$$

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:

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

The observed production rate of caustic soda is expressed as:

$$\dot{m}_{OS} = C_{OS}\dot{V}_{OB} \qquad (19)$$

Therefore the observed operational current efficiency is given as:

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

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

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

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

$$\text{Yield} = \frac{\dot{m}_{OS}}{\text{inlet mass flow rate of brine feed}} \qquad (24)$$

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

4. Results and Discussions

The values of current, mass flow rate, efficiency and so on obtained for the two cells closely resemble the range obtained for diaphragm cells operated by stepped down a.c to d.c rectified power supply from mains (Olufemi *et al.*, 2010). The experimental results had been reported (Olufemi et *al.*, 2011). The prediction of experiment by simulation was encouraging. Experimental values are represented by markers, while continuous and dotted lines represent modeled values.

Figure 3 shows the variation of average current with average voltage for the asbestos and non-asbestos diaphragm cells. Higher currents and voltages were observed for the asbestos diaphragm cells. The two cells confirmed the ohmic direct proportional relationship that current increases linearly with voltage. The non-asbestos seems to have a higher operational electrical resistance with respect to the present operation. The range of negative and positive deviations of simulated from experimental values was between -5 and +6%. respectively.

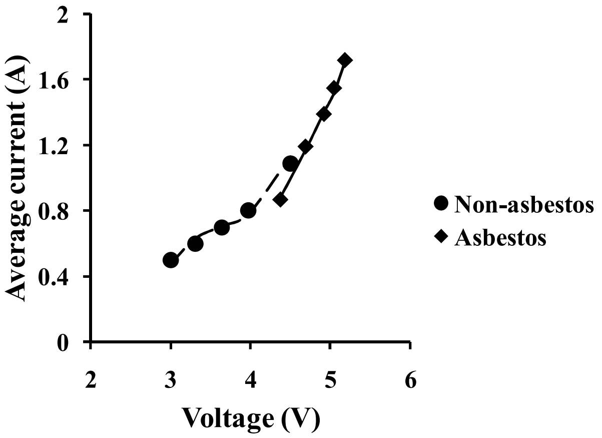

Figure 3: Variation of current with voltage for the asbestos and non-asbestos diaphragm cells.

In Figure 4, the molar concentration of caustic soda in the catholyte products of the two cells is shown to increase with average cell current. The non-asbestos diaphragm cell produced more concentrated solutions relatively than the asbestos diaphragm cell with respect to the present electrochemical operation. Despite the fact that the non-asbestos cell operated at a lower electrical current than its counterpart, it still produced more concentrated products. The non-asbestos diaphragm cell seems to be better in the production of more concentrated product in this regard. The reason may be due to the fact that the non-asbestos diaphragm is less permeable than the asbestos diaphragm 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 simulated values matched the experimental values closely, with highest deviations between -6% and +7%.

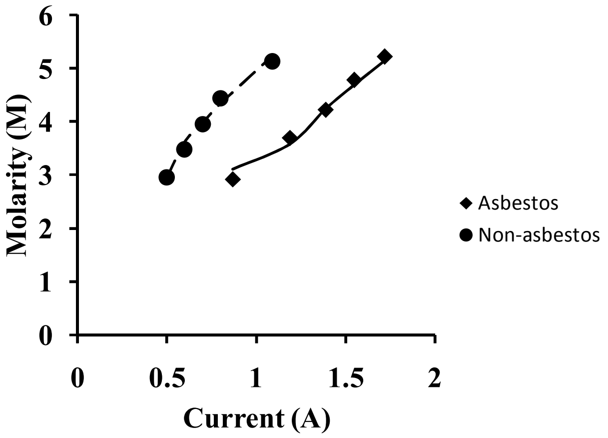

Figure 4: Variation of molar concentration with current for the asbestos and non-asbestos diaphragm cells.

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, the asbestos diaphragm cells resulted in higher mass flow rate than the non-asbestos cell. This follows directly from the fact that the asbestos diaphragm is more permeable in the present operation. However it can be observed in the two 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, for which modeling will play a key role. The model prediction was seems good with deviations ranging between -6% and +8%.

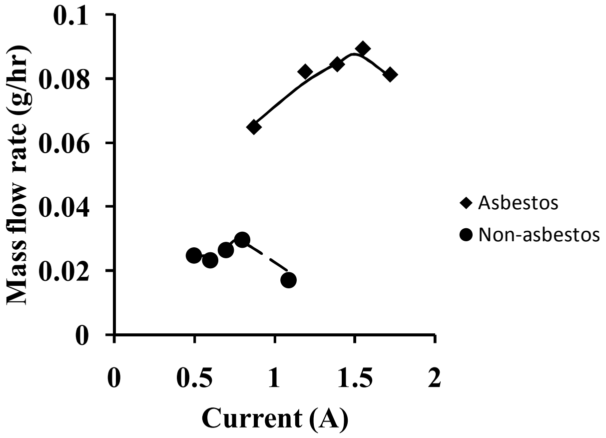

Figure 5: Variation of mass flow rate with current for the asbestos and non-asbestos diaphragm cells.

Figure 6 shows the variation of average current efficiency with operational voltage. As it can be deducted from the operation of the two cells, too high voltages above the theoretical decomposition voltage leads to reduction in efficiency, there by resulting in more energy wastage. The asbestos diaphragm cells recorded higher current efficiencies with respect to the present operational procedure. The less permeable nature of the non-asbestos diaphragm may be responsible for its lower current efficiency relative to its counterpart. The experimental operation was closely matched by the simulation with deviations between -6% and +7%.

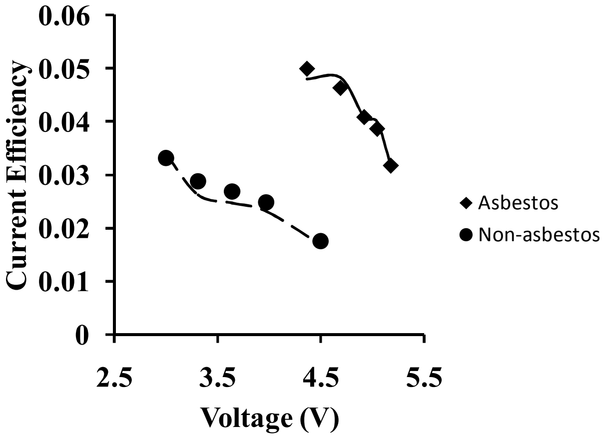

Figure 6: Variation of current efficiency with operational voltage for the asbestos and non-asbestos diaphragm cells.

The yield (kg NaOH / kg NaCl input) increased with voltage in Figure 7, with that of the non-asbestos cell indicating higher yield with respect to voltages applied. This showed the possibility of improving the yield of caustic soda produced with increased operational voltages for the cells. This observation was closely revealed by the simulation from the plots. The simulation deviations observed was between -6% and +7%.

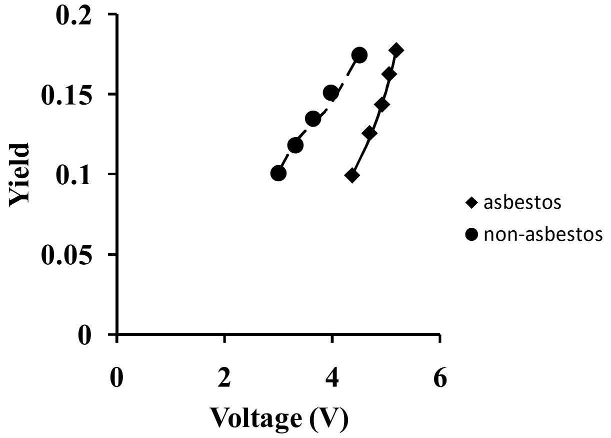

Figure 7: Variation of yield with operational voltage for the asbestos and non-asbestos diaphragm cells.

In Figure 8, from the variation of yield/d.c. Watt with yield, the non-asbestos cell showed a better yield per d.c Watt than the asbestos diaphragm cell. This indicated that the non-asbestos cell in the present operation produced more desired product than the asbestos cell 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. Experimental results were closely predicted by their simulated counterparts with deviations ranging between -6% and +8%..

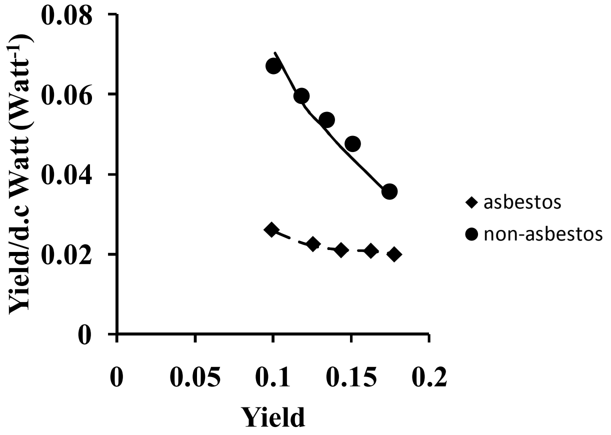

Figure 8: Variation of yield with yield /d.c Watt for the asbestos and non-asbestos cells.

In Figure 9, the variation of the specific electrical energy requirement for the production of caustic soda with respect to operating voltage is shown. The present model and simulation predicted the cell operation very well, as the maximum negative and positive deviations of all simulated from experimental data was between -0.06 and +0.08 respectively. It can be deduced that the specific electrical energy needed to produce 1 kg of caustic soda decreased with operating voltage for the two cells. The specific energy required by the non-asbestos diaphragm cell for corresponding voltages with that of the asbestos diaphragm cell seems to be lower. This is a strong indication that the non-asbestos diaphragm cell has a higher capability of producing more caustic soda for the same electrical energy supplied with its asbestos counterpart. In simple terms, the non-asbestos diaphragm cell produced more caustic soda for the same applied potential difference than the asbestos diaphragm cell in the present operation. 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/m^2 (Worell *et al.*, 2000; Tilak *et al.*, 2007).

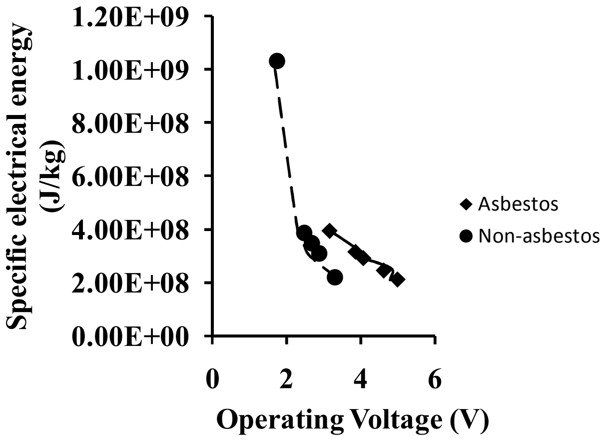

Figure 9: Variation of specific electrical energy with operational voltage for the asbestos and non-asbestos diaphragm cells.

The two laboratory scale cells presented here required higher specific energy per kilogram of caustic soda produced in the present operation. The operational current densities employed in the solar powered cells ranged from 52.08 to 179.17 A/m^2, 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. This will definitely rely upon the modeling and simulation in this work.

5. Conclusions

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 +0.08 and -0.06 respectively. It can be reasonably concluded that 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. It is not constant also, but depends on the variable sun's intensity.

Quantitative analysis showed that the quantity and concentration of caustic soda produced varied with the current and voltage obtained from the solar panels which were directly depend on the intensity of the sun on any particular day and the length of time the panels were exposed to sunlight. On comparison of the types of diaphragms used, the non-asbestos diaphragm seems to be preferable, because its yield and productivity is comparatively better to that of the asbestos diaphragm. It could also be less harmful compared to the carcinogenic nature of asbestos.

With further research on appropriate scale-up and optimization techniques, which will rely greatly on modeling and simulation, solar powered cells could possibly match commercial scale conventional cells in certain performances. The maximum current density employed experimentally was 179.17 A/m^2 for the two 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. The simulation presented can also be utilized for better design, operation and process optimization.

Acknowledgement

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Notation

A_A, A_{AC}, A_C, A_D, A_{EL}, A_{IA}, A_{IC} = Area (m^2)

∇C = Concentration change (mol).

D = Hydroxyl diffusion coefficient

D_P = Pore Diameter (m)

EL = Pore Length (m)

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

F = Faraday's Constant (C/mol)

g = Acceleration due to gravity (m/s^2)

h_t = Height of anolyte (m)

I_{MD}, I_{OB}, I_{MN} = Current (A)

l_D = Diaphragm thickness (m)

l_S = Distance between electrodes (m)

k = Average electrolyte specific conductivity ($Ohm^{-1}m^{-1}$)

m = Ionic 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/m^2)

P_{MD} = Modelled Power (Watt)

R_m = Resistance (Ohm)

r_{RA}, r_{RC} = Reaction rate (mol/m^2s)

T = Temperature (K)

t = time (s)

v, V = Volume (m^3), Voltage (V)

$\dot{V}_D$, $\dot{V}_{OB}$ = Volumetric flow rate (m^3 / s)

vs = Superficial velocity (m/s)

w = Percentage weight

z = Electron Charge (C)

Greek Alphabet

ρ = Resistivity (Ohm.m)

ρ_{EL} = Density of electrolyte(kg/m^3)

τ = Tortuosity factor

ε = Porosity

Λ = Equivalent Conductance (Ohm^{-1} m^2)

η = Overvoltage (V)

η_{MD}, η_{OB} = Current efficiency

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