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Harvesting Sustainable Energy from Saltwater: Part II – Effect of Electrode Geometry

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Abstract

Green energy or renewable energy is a widely and commonly used terminology when depicting the energy generated from natural resources such as solar, wind, geothermal, biomass and hydropower. One energy resource, in particular, has yet to unleash its potential is the saltwater energy. When salt is dissolved in the water, the ionic compounds of sodium and chlorine are separated, thus allowing the free movement of ions in the solution. This study is the second part of the development phase in producing a low cost saltwater lamp for rural and remote communities in Malaysia. This study specifically focuses on the dimension and geometry of the aluminium electrodes as well as the types of carbon electrodes used. This study is important in determining the most cost effective electrodes to be used in the saltwater lamp.

Keywords: *Renewable Energy; Saltwater Energy; Green Technology; Electrodes;*

1. Introduction

Nowadays, as the world is peeking into Industry 4.0 where advanced digitalization of manufacturing management and chain production is been showered with attention, renewable energy has never ceased to be the utmost impactful agenda in the global energy sector as reported by World Energy Issues Monitor 2018 [1]. Green energy or renewable energy is a widely and commonly used terminology when depicting the energy generated from natural resources such as solar, wind, geothermal, biomass and hydropower.

Malaysia particularly is not falling behind in ensuring constant supplies of energy to meet the country's demand while preserving the

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environment. As shown in Fig. 1, Malaysia is creating a greener future for the society by gradually promoting electric vehicles as well as continuous efforts on hydropower, solar energy, biomass and biogas. These incentives are aligned with the country's mission to facilitate 50% of energy transition from fossil fuel to renewable energy by 2050 [1]. The country's commitment in becoming a low carbon energy producer is applaud able. However, in order to spur the growth of renewable energy sector, Malaysia must exploit the inexhaustible energy resources available and not restricted to hydropower, solar energy, biomass and biogas. One energy resource, in particular, has yet to unleash its potential is the saltwater energy.

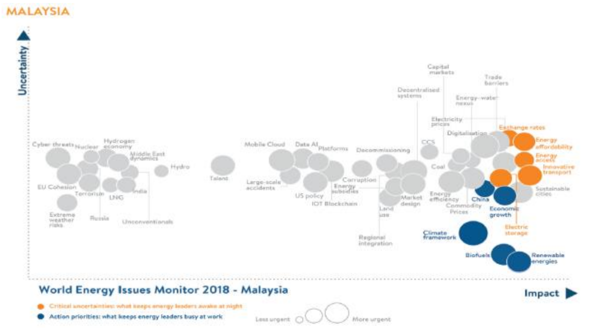

Figure 1: Malaysia's energy agenda in 2018. Used by permission of the World Energy Council [1]

Salt water solution that comprises of salt or sodium chloride (NaCl) and water is a conductive solution due to the presence of both positively charged (Na+) and negatively charged (Cl-) ions as well as H2O molecules. When salt is dissolved in the water, the ionic compounds of sodium and chlorine are separated, thus allowing the free movement of ions in the solution. To generate saltwater energy, two dissimilar metals are used to produce free electrons when immersed in the saltwater solution. The movement of sodium and chlorine ions will assist the flow of electrons in the solution from one electrode to another electrode which eventually generate electric current to power up a load connected at the external circuit. Theoretically, the generation of electric current is the result of continuous flow of electric charge carriers. Therefore, the presence of salt in the solution is to act as a bridge or conductor for the electrons to travel from cathode to anode.

This process is the underlying principle of galvanic cell, whereby the electric current generated varies with the type of electrodes used. This is because the behavior of metals in the saltwater solution largely depends on the reactivity of the metal i.e. its susceptibility to dissolve when in contact with the salty solution. There are also other intrinsic and extrinsic factors [2-6] that contributed to the amount of electric current generated which becomes the motivation of this study. Previously in [2], investigation on the performance of the saltwater energy generation has been conducted to observe the effect of salinity concentration, electrodes combination, number of cells and electrode's durability in a saltwater solution. It was found that the Aluminium (Al) and Carbon (C) electrodes combination produced the highest voltage output especially when connected in series with more than 2 Al-C cells. This is due to the reactivity properties of both materials as can be observed in the durability test. In all cases, the amount of voltage produced is not linearly proportional to the salinity concentration. To further investigate the electrical properties of the electrodes, this study focuses on the dimension and geometry of aluminium electrodes and the types of carbon electrode used. This study is the second part of the development phase to produce a low cost saltwater lamp for rural and remote communities in Malaysia.

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2. Methodology

The type of electrode combination that can produce the highest voltage output, i.e. Aluminium (Al) and Carbon (C) electrodes combination has been identified previously in [2]. Deeper investigations on the size of electrodes and its surface area (that are in contact with the saltwater solution) are conducted to observe the electrical properties of these parameters. Figure 2 below depicted the general experimental setup of this study. For this experiment, two galvanic cells are used and connected in series to increase the voltage produced. Each cell contains 17 gram of salt, which is dissolved in 500ml of tap water. Thus the salinity of the salt water is about 3.4% or 34 gram/litre. This is very close to the average salinity of seawater, which is about 3.5% or 35 gram/litre. Aluminum and carbon electrodes are placed in each cell. The total voltage and current generated from the cells are measured using Sanwa digital multimeter. The readings of voltage and current are recorded at 1 minutes and 5 minutes upon the commencing of the experiment using multimeter. The saline solution is stirred occasionally. To ensure the validity of the results obtained, new saline solution and electrodes are used each time to prevent the effect of residual charges from previous experiment on the measurement recorded. The design of the salt water galvanic cell is similar to a battery cell with salt water as the electrolyte. With any battery, the main function of it will be to supply electrical energy to the load.

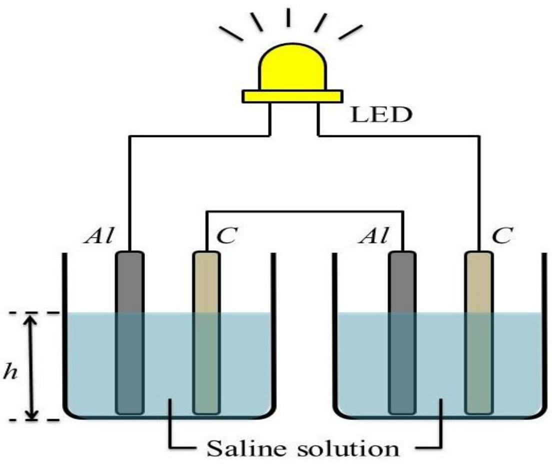

Figure 2: General experimental setup of saltwater galvanic cell

2.1 Geometry and surface area of electrodes

In this experiment the effect of geometry and surface area of immersed electrodes on the voltage and current generated from the galvanic cells is observed. The types of electrodes investigated are Aluminium (Al) and Carbon (C) as shown in Fig. 3. Two different sizes of hollow cylinder-shaped aluminium rods are used with carbon rod as anode. Each electrode is approximately 8 cm in length. All rods are immersed in saline solution such that the height of the solution, *h*, that is in contact with the electrodes surface is 5 cm. The experimental procedures follow the general procedures of measuring the voltage and current output. The material properties for this experiment are as shown in Table 3 where the abbreviations for all electrodes used are defined. The electrodes combinations under investigation are as follows; $A_{hollow\_0.5}$ - $C_{solid\_0.5}$, $A_{hollow\_0.5}$ - $C_{solid\_1.0}$, $A_{hollow\_1.0}$ - $C_{solid\_0.5}$, $A_{hollow\_1.0}$ - $C_{solid\_1.0}$, $A_{solid\_1.5}$ - $C_{solid\_0.5}$, and $A_{solid\_1.5}$ - $C_{solid\_1.0}$.

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Figure 3: Aluminum electrodes used in experiment.

Table 1: Floating-point operations necessary to classify a sample

Material	Symbol	Dimension		Supplier
		Diameter (inch)	Length (cm)	
Al (hollow cylinder)	$A_{hollow\_0.5}$	0.5	8	RS Components
Al (hollow cylinder)	Ahollow_1.0	1.0	8	RS Components
Al (solid rod)	Asolid_1.5	1.5	8	RS Components
C (solid rod)	Csolid_0.5	0.5	8	Henan Zion New Material Ltd (China)

2.2 Types of Carbon

In this experiment, the effect of the types of carbon used as electrode (i.e. cathode) on the voltage and current output is observed. There are many types of carbon-impregnated materials available in the market. In this experiment, carbon impregnated materials such as fabric, felt, paper and sponge are used as electrode as shown in Fig. 4. Activated carbon powder as well as carbon rod are also used for comparison. The activated carbon powder was grinded and spreaded over a conductive mesh before submerged in the saline solution. The size of each material is carefully measured to be as closed as 0.5 inch in width and 8 cm in length. The size of Al electrode rod is 0.5 inch diameter x 8 cm. The material properties of each carbon electrode can be found in Table 2 where the abbreviations of all electrodes used are defined. The experimental procedure follows the general procedure of measuring the voltage and current output.

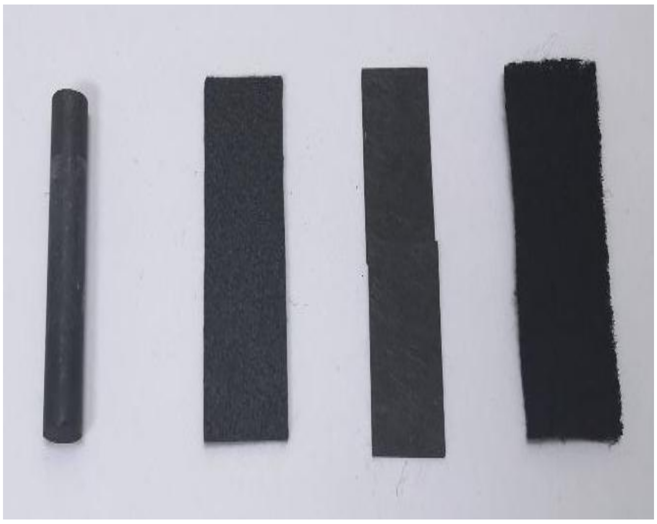

Figure 4: Types of carbon impregnated materials used in experiment

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Table 2: Material properties for aluminium and carbon electrodes

Carbon Electrode	Symbol	Dimension		Supplier
		Width (inch)	Length (cm)	
Carbon impregnated fabric	Cfabric	0.5	8	Boshang Zhejiang
Carbon impregnated felt	Cfelt	0.5	8	Good Great Shenzen

3. Results and Discussions

3.1 Geometry and surface area of electrodes

The results for this experiment are tabulated in Table 3. The results are the measurement of voltage (V) and current (mA) produced at 1 and 5 minutes at the commencement of every experiment for all combinations. In general, voltage output decreased slightly as the time duration of the experiment increased. This is true for all electrodes' combinations. This is also in agreement with the current output where the current output reduced with the duration of the experiment as depicted in Fig. 5. It is apparent from the results obtained that using hollow cylindrical aluminium rod of 2-inch outer diameter ($A_{hollow\_2.0}$) produced higher voltage output when combined with solid cylindrical carbon rod of the same diameter ($C_{solid\_1.0}$). The lowest voltage output was produced by the combination of $A_{solid-1.5}$ and $C_{solid-0.5}$.

Table 3: The effect of surface area on voltage and current produced

Electrodes	$C_{solid\_0.5}$				$C_{solid\_1.0}$			
	V (V)		A (mA)		V (V)		**A (mA)**	
	1 min	5 min	1 min	**5 min**	**1 min**	5 min	**1 min**	5 min
$\boldsymbol{A_{hollow\_1.0}}$	1.55	1.49	**8.6**	**7.7**	1.57	1.51	**4.0**	**2.8**
$\boldsymbol{A_{hollow\_2.0}}$	1.56	1.50	9.0	7.8	**1.59**	1.52	4.2	2.9
$A_{solid\_1.5}$	1.41	1.30	11.4	9.5	1.46	1.39	5.6	3.6

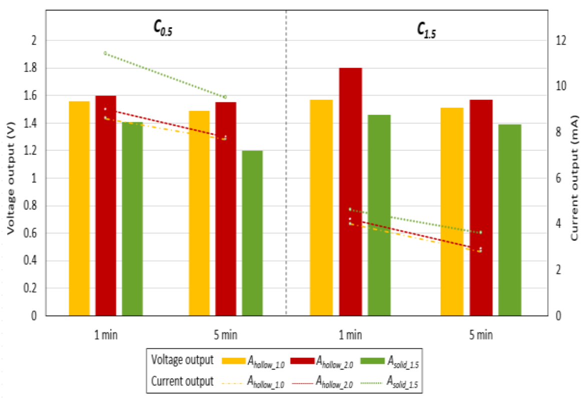

Figure 5: Experimental result for the effect of electrode geometry and surface area on voltage and current produced

As can be seen in all experiments, the voltage and current output decreased as the time duration of the experiment increased from 1 minute to 5 minutes. This is one of the discharge characteristics of a cell battery that depends on the chemistry of the battery, i.e. the types of electrodes used for anode and cathode. Different battery chemistries have different discharge characteristics in terms of its nominal cell voltage and discharge curve as shown in Fig. 6. For example, a flat discharge curve such as displayed by Ni-Cd and NiMH suggests a constant voltage output throughout the discharge cycle. A more steep discharge curve

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as such Zn/MnO2 demonstrates a substantial drop in voltage output as the battery discharges. A high drop in voltage output during discharge cycle could disturb the functionality of any electrical applications that require a stable constant voltage supply. One possible solution to mitigate this problem is by incorporating voltage regulator in the circuit to provide more stable supply. Other factors that can contribute to the discharge characteristics are cell temperature, the state of charge and the age of the cell [7-10].

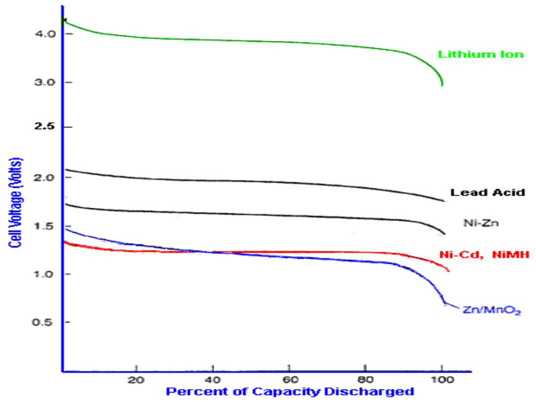

Figure 6: Battery performance characteristics. Used by permission of The Electropedia [10]

The geometry and surface area of the electrodes play an important role in varying the current output of the galvanic cell. It is anticipated that the larger the surface area, the larger the current output with little to no changes in the voltage output. The cell voltage is determined by the relative potential of the metals used and does not depend on the dimension of the electrodes. For galvanic cell, the internal resistivity is inversely proportional to the surface area of the electrode ($R \propto \frac{1}{Area}$). Thus, larger surface area will decrease the internal resistivity value of the cell, which eventually increases the current output and the allowable maximum current. Having larger surface area of the electrodes will also allow for greater contact between the ions and the electrode's surface, thus promotes the reaction rate. Increasing the surface area is comparable to the characteristic of a parallel current source, whereby the voltage output remains the same but the total current output adds up.

Theoretically, the hollow cylindrical aluminium rod of 1-inch outer diameter ($A_{hollow\_1.0}$) is expected to produce higher current output when combined with solid cylindrical carbon rod of the same diameter ($C_{solid\_1.0}$) as a result of larger surface area and greater contact with ions as shown in Fig. 7(a). The electrode's surface area for hollow and solid rod is calculated based on Fig. 7(b):

The total area surface for hollow rod,

$$T_{hollow} = \pi R^2 - \pi r^2 + 2\pi Rh + 2\pi rh \quad \textbf{(1)}$$

The total area surface for solid rod,

$$T_{solid} = \pi R^2 + 2\pi Rh \quad \textbf{(2)}$$

Where R and r are the external and internal radii respectively and h is the length of the rod that is being submerged in the saline solution. The dimension and calculated surface area are as tabulated in Table 4 where the symbol of surface area for all electrodes used is introduced.

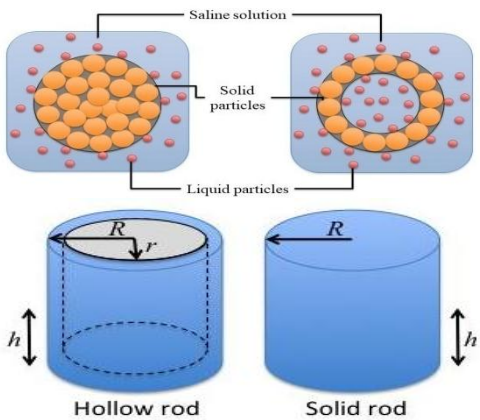

Figure 7: (a) Larger surface area of the electrode allows greater contact with the ions, and (b) dimension for hollow and solid rods

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Table 4: The dimension and surface area of hollow and solid electrodes under investigation

Electrodes	R (cm)	r (cm)	h (cm)	T (cm^2)	Symbol for surface area
$A_{hollow\_1.0}$	1.27	0.97	5	72.48	$TA_{hollow\_1.0}$
$A_{hollow\_2.0}$	2.54	2.24	5	154.67	$TA_{hollow\_2.0}$
$A_{solid\_1.5}$	1.91	-	5	71.47	$TA_{solid\_1.5}$
$C_{solid\_0.5}$	0.64	-	5	21.39	$TC_{solid\_0.5}$
$C_{solid\_1.0}$	1.27	-	5	44.96	$TC_{solid\_1.0}$

The ratio of surface area for $TA_{hollow\_2.0}$: $TA_{hollow\_1.0}$: $TA_{solid\_1.5}$ is 2.1 : 1.01 : 1 and for $TC_{solid\_1.0}$: $TC_{solid\_0.5}$ is 2.1 : 1. The surface area for $A_{hollow\_2.0}$ is undoubtedly double the surface area for $A_{hollow\_1.0}$ and $A_{solid\_1.5}$. Therefore, it is predicted that the current output for $A_{hollow\_2.0}$ will be higher than $A_{hollow\_1.0}$ and $A_{solid\_1.5}$ if not double. Looking at the result in Table 3, the assumption is validated for $A_{hollow\_2.0}$ and $A_{hollow\_1.0}$ where the former produced higher current output than the latter, albeit the differences rather small. Surprisingly, $A_{solid\_1.5}$ was found to produce much higher current output than $A_{hollow\_2.0}$ and $A_{hollow\_1.0}$, which contradicts with the expectation mentioned earlier. A possible explanation for this unanticipated result could be due to the decreased in electrical resistance of the $A_{solid\_1.5}$ as well as its saline solution. This is supported with the large reduction in the nominal voltage output of $A_{solid\_1.5}$. The most interesting finding was the behavior of current output when carbon electrode of larger diameter (in this case $C_{solid\_1.0}$) was used. Contrary to expectation, the results of $C_{solid-1.0}$ in Table 3 show a drastic dropped by more than half in current output as compared to that when $C_{solid-0.5}$ was used. Nonetheless, the voltage output did not vary much, albeit a little bit higher. This phenomenon is observed in all electrodes under investigation with $C_{solid-1.0}$ as the cathode. The only logical explanation for this contradictory result may be due to the distance between the electrodes when placed in the saline solution. Increasing the distance will increase the internal resistance in the solution thus affect the current output.

3.2 Types of carbon

The results for this experiment are tabulated in Table 5. The results are the measurement of voltage (V) and current (mA) produced at 1 and 5 minutes at the commencement of the experiment. The measurements were recorded for each type of carbon electrodes under investigation with aluminium rod of 0.5 inch diameter as the anode. In general, all voltage measurement showed a decreased in voltage output as the duration of experiment increased. The same phenomenon was shown in current output for all carbon electrodes. Again, the results essentially demonstrated the discharge characteristics of a battery. Carbon impregnated materials such as activated carbon, carbon felt, carbon rod and carbon nano tubes were among other cathode substrates that are usually being used in electrochemical process [11-13]. It is interesting to note that the highest voltage output was produced by C_{sponge} at 1.92 V but there were no current detected from the electrode, thus the LED did not emit any light. A possible explanation for this is that an open circuit occurred within the electrical circuit thus no current flowed in the LED. The highest current output was produced by C_{paper} at 17.3 mA, however surprisingly showed a constant voltage output throughout the experiment. This

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can be a good electrode combination for a longer lasting saltwater lamp. C_{rod} also generated high voltage at 1.76 V with 8 mA current output at the first minute of the experiment. Meanwhile C_{fabric} generated the second highest current output but with lower voltage output. $C_{activated}$ produced the lowest voltage and current output thus was deemed not suitable for long term application. This is quite unexpected since activated carbon has been frequently used in saltwater electrical generation system. Although all carbon electrodes under investigation are made from carbon, it is expected that at least the voltage output does not vary that much since voltage depends on the ability of the free electrons to travel through external circuit from anode (aluminium electrode) to cathode (carbon electrode). This discrepancy might be caused by the composition of the carbon electrodes as well as the reaction rate of the material. Further investigation on the molecule structure of these materials must be undertaken before a firm conclusion can be made.

Table 5: The effect of types of carbon on voltage and current produced

Electrodes	V (V)		A (mA)	
	1 min	5 min	1 min	5 min
C_{fabric}	1.42	1.36	**10.2**	**9.7**
C_{felt}	1.24	0.88	7.6	7.2
C_{paper}	1.52	1.52	17.3	15.5
C_{sponge}	1.92	1.80	0	0
$C_{activated}$	1.07	0.63	0.2	0.1
C_{rod}	1.76	1.73	8.0	7.1

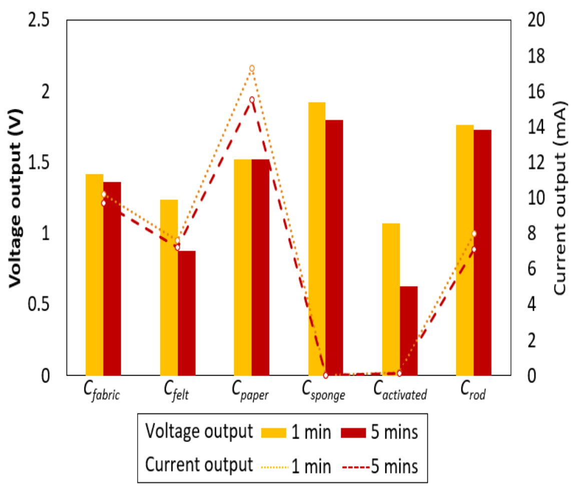

Figure 7: Experimental result for the effect of types of carbon electrodes on voltage and current output

4. Conclusion

The present study was conducted to determine the effect of dimension and surface area of electrodes as well as the type of carbon electrodes used on the performance of the saltwater energy generation, which is a part of saltwater lamp product development. In all experiments, the results are in agreement with the discharge characteristics whereby voltage output decreases as the time of experiment increases. However, while investigating the effect of surface area, the results showed a contradictory finding whereby the current output dropped by more than half for larger surface area. This requires further investigation to determine the actual causes of this phenomenon. In observing the effect of types of carbon electrodes, carbon impregnated paper exhibits a good electrode combination for a longer lasting saltwater lamp. However, further investigation on the molecule structure of these materials must be undertaken before a firm conclusion can be made.

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