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EMPIRICAL EQUATIONS RELATED TO ELECTRICITY GENERATION FROM SALT WATER: CONTRIBUTION TO RENEWABLE ENERGY

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ABSTRACT

This paper provides some empirical equations that pertain to electricity generation from saline solution. The data used in this study was taken from the Table of Conductivity vs Concentration for Common Solutions and from the laboratory results in salinity loss and voltage applied. The data on salinity and conductivity of sodium chloride (NaCl) were used in the analysis. The empirical equations derived in this paper showed that the basic electricity quantities, namely, voltage, resistance, and current are in a power-law relationship with water salinity. The power law relationships enable the computation of these quantities given water salinity. Resistance is in an inverse power law relationship with water salinity; salinity is in an inverse power relationship with a voltage applied, and current is in direct power law relationship with salinity. Laboratory-scale results as translated into mathematical models can be used as the basis for planning industrial-scale salinity-based power generating plants. The prospects of establishing such power-generating plants in Philippine coastal communities are posed as a challenge to non-government organizations and rural cooperatives.

Keywords: empirical equations, Ohm’s law, power-law, sodium chloride, salinity, electricity

Introduction

Electric power generation using readily available chemicals is one area of study in renewable energy. In particular, Loeb (1973) investigated the possibility of harvesting the energy of mixing of two aqueous solutions (salt and fresh water) represented by the Jordan River and the Dead Sea to produce electricity. Thus, was born the concept of Salinity Gradient Power (SGP) which is the energy available derived from the difference in the salt concentrations between seawater and river water. More recently, Brogioli (2009) introduced the capacitive method where energy is extracted by the mixing of salt water and freshwater by cyclically charging up electrodes in contact with saline water followed by a discharge in freshwater. The difference in energy needed for the charging and discharging steps produces electrical energy. An electronic explanation of this phenomenon is that capacitance is a function of ion density. By introducing a salinity gradient and allowing some of the ions to diffuse out of the capacitor, the capacitance is reduced, and so the voltage must increase since the voltage equals the ratio of charge to capacitance. This paper provides some empirical equation that pertains to electricity generation from saline solution.

The Philippine is an archipelagic country consisting of over 7,100 islands. The concentration of population is found mainly in coastal communities so that the idea of generating electricity from the vast seas and oceans surrounding the islands is greatly appealing. Generating electricity from seawater, taking advantage of its high salinity, is a "green and renewable" option because it requires no fuel and produces no harmful gases or liquid by-products, unlike the more established SGP (Salinity Gradient Power) methods. The technology is still at its infancy stage and has only been tested in laboratories (Brogioli, et. al 2009; Brogioli 2009).

Laboratory experimentation conducted for the purpose of harvesting electrical energy from saltwater yielded a wealth of information on the phenomenon (Gibson Research Corporation, 1999; Brogioli, 2009; Ten-Hang Meen et al., 2014). In order to further advance this technology, it is important that this information be organized and formulated as a mathematical model. In turn, the mathematical model that will be derived can be utilized to infer how the laboratory-scale results can be replicated up to industrial scale and, thus, become useful to society.

Empirical Model Development

The data on salinity and conductivity of sodium chloride from Gibson Research Corporation (1999), Table of Conductivity vs Concentration for Common Solutions, were used for analysis (Table 1). The analysis proceeds by determining the function that best describes the relationship between the concentration of sodium chloride (in parts per million) and conductivity (microsiemens/cm).

The graph of conductivity versus salinity shows a linear pattern with a large gap towards the tail of the regression line. Fig. 1 performed some transformations to accentuate the linear relationship.

Table 1: Conductivity of NaCl at various concentrations

ppm salinity	NaCl conductivity
1	2.2
3	6.5
10	21.4
30	64.0
100	210.0
300	617.0
1000	1990.0
3000	5690.0
10000	17600.0
30000	48600.0
50000	78300.0
100000	140000.0
200000	226000.0

Source: Gibson Research Corporation (1999)

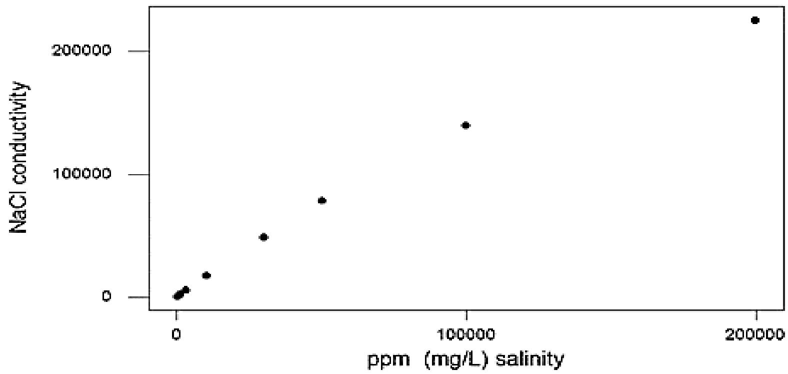

Figure 1: Relationship between NaCl Salinity & Conductivity

The logarithm of conductivity and salinity of NaCl were plotted to accentuate their linear relationship (Fig. 2).

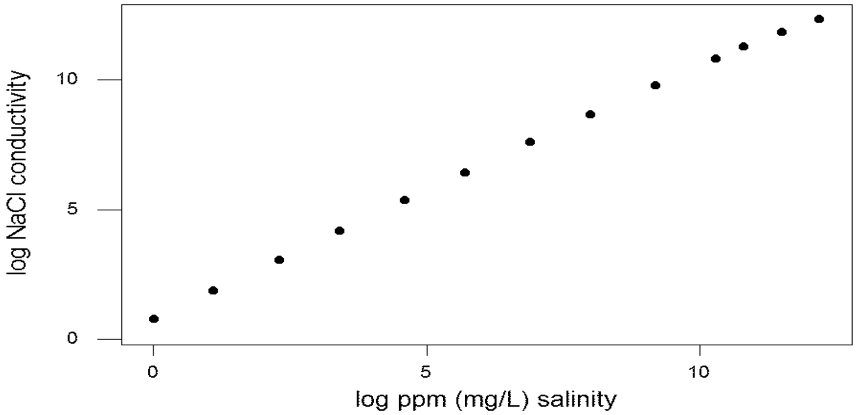

Figure 2: The relationship of NaCl salinity and Conductivity plotted using their logarithms

The straight line pattern is now more pronounced. Using a simple linear regression model, the corresponding regression equation is obtained as:

Log (conductivity) = 0.890 + 0.957log (salinity)

with an R^2 value of 99.90%.

Equivalently, we can write:

Conductivity (Y) = 2.43513(salinity)$^{0.957}$.

Hence,

$$Y = 2.43513(S^{0.957}). \quad (1)$$

where S = salinity.

The classical Ohm's law states that the electromotive force (E) is equal to the product of current (I) and resistance (R). That is:

$$E = IR. \quad (2)$$

The resistance (R) and conductivity (Y) are inversely related:

$$R = 1/Y \quad (3)$$

It follows that for a sodium chloride solution with salinity (S), we obtain

$$E = 0.410656(I)(S^{-.0957}) \quad (4)$$

Equation (4) provides an empirical solution to obtaining the electromotive force E given the salinity level (S). On the other hand, Equation (1) suggests that the higher the salinity level, the higher becomes the conductivity of a sodium chloride solution (hence, the smaller the resistance).

Ten-Meen *et al*. (2014) conducted an experiment where various voltage sources were applied to a saline solution and measured the drop in salinity. Brogioli (2009) capacitive model suggests that the electromotive force is generated because of the salinity gradient between salt water and fresh water. The greater the difference or gradient, the higher becomes the electromotive force. For instance, a 24 ppt (2 tablespoon of pure salt mixed with 1 liter of fresh water) produces an electromotive force of 2 volts. However, the relationship between salinity gradient and the electromotive force is not a monotonic increasing relationship. It is clear that when the salinity of the solution reaches a certain value, the electrical energy peaks and then starts to descend i.e. as freshwater content becomes overwhelmed by pure NaCl. The table below shows the data obtained by the Ten-Hang Meen et al. (2014) experiment.

Table 2: Salinity Reduction as a Function of Voltage Applied

Voltage	Salinity
0.0	36.0
2.5	32.5
3.0	31.0
4.0	30.0
5.0	29.0
6.0	28.0
7.0	27.0
8.0	26.5
9.0	26.0
10.0	25.5
11.0	25.0
12.0	25.0
13.0	25.0

Source: Ten-Hang Meen *et al*. (2014). Innovation in Communication and Engineering

The plot of salinity as a function of voltage is shown below:

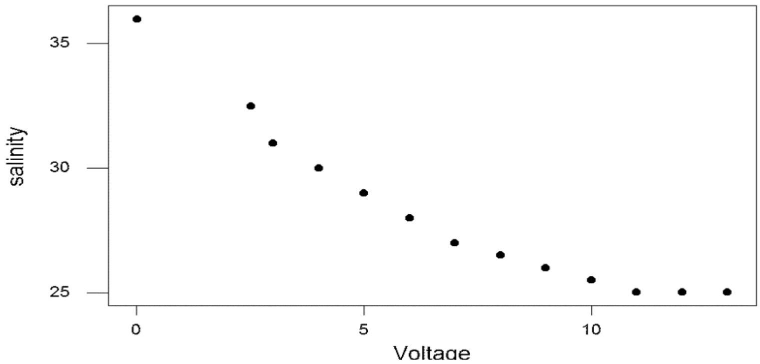

Figure 3. Salinity versus electromotive force

Experimental data suggest that as the voltage applied to a saline solution increases, the solution's salinity decreases in a power-law type of relationship. The salinity loss decreases the solution's conductivity (Equation 1) thereby increasing resistance. The graph of log(voltage) versus log(salinity) is shown below:

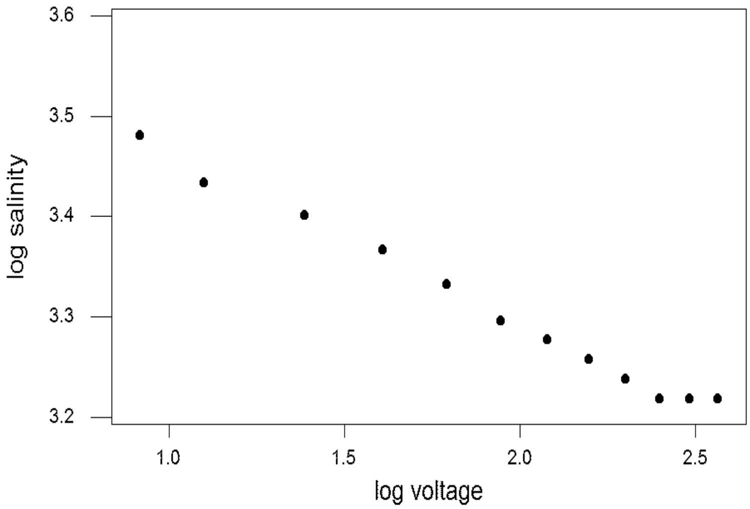

Figure 4: Graph of log(voltage) versus log(salinity)

The logarithmic transformation shows a straight line pattern except at the tail of the graph where there appears to be a saturation or leveling off.

The regression equation is given by:

log salinity = 3.63 - 0.165 log voltage (5)

The squared correlation coefficient is given by R-squared = 99.1%.

Equation (5) can also be written as:

$S = C^*(V^{-.165})$ (6)

where S represents salinity and C is a constant , C = exp(3.63) =37.7128

The predicted salinity when a 12-volt force is applied can be obtained from Equation 6:

$S = 37.7128^*(12^{-.165}) = 25.0729$ ppt.

For ease of mathematical computations, let V = EMF, then Equation (6) can be solved for V as follows:

$$V = (\frac{C}{S})^{6.0606} \quad (7)$$

We can then develop a mathematical model for inferring the current generated by a saline solution from a mere application of Equations (4) and (7) as follows:

$$I = \frac{V}{R} \quad (8)$$

Now, $V = K_2 S^{-\beta}$ and $R = K_1 S^{-\alpha}$, hence:

$$I = \frac{K_2 S^{-\beta}}{K_1 S^{-\alpha}} = K S^{\alpha-\beta} \text{ where } K = \frac{K_2}{K_1} \text{ and S = salinity } (9)$$

Equation (9) can be used to determine the salinity required to produce a current of magnitude I.

Discussion

The empirical equations derived in the previous section can be used as the basis for the development of a salinity-based power generation system, particularly in the coastal communities. The Philippines is an archipelagic country, hence, technology can be put to advantageous leverage.

However, in order for the technology to be fully adopted at the community level, it is necessary that the issues of reliability and long-term sustainability of the generated electric power to be fully studied and investigated. Likewise, discussions on the economic comparative advantage of the salinity-based power generation over the other green alternatives are comprehensively tackled by research scientists.

On the establishment of a Salinity-Based Power Generation Plant at the community (barangay) level, the present legal framework prohibits the State from investing in any power-generation schemes (under the Electric Power Industry Reform Act or EPIRA law) to avoid competition with the private sector. Consequently, such a venture can be given to Non-Government Organizations (NGO's) operating in the rural communities. Likewise, community cooperatives can initiate the establishment of Salinity-Based power Generation Plants in the coastal towns of the country as part of the mandate of all rural cooperatives under the Cooperative Development Act.

The role of the academe in this transfer of technology schema will be to provide the technical and scientific expertise in order to ensure that such a technology will be optimally utilized by the rural communities. As a first step towards this objective, the academe can translate the technical aspects of this paper in lay-man's terms so that the stakeholders can fully appreciate the value of the technology.

Conclusion

The empirical equations derived in this paper showed that the basic electricity quantities, namely, voltage, resistance, and current are in a power-law relationship with water salinity. The power law relationships enable the computation of these quantities given water salinity. In particular, resistance is in an inverse power law relationship with water salinity; the salinity is in an inverse power relationship with a voltage applied; and current is in direct power law relationship with salinity.

Laboratory-scale results as translated into mathematical models can be used as basis for planning industrial-scale salinity-based power generating plants. The prospects of establishing such power-generating plants in Philippine coastal communities are posed as a challenge to non-government organizations and rural cooperatives.

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