

## TITLE OF THE INVENTION

### MULTI-STAGE DIFFUSION DIALYSIS SYSTEM UTILIZING E.M.F POTENTIAL DIFFERENCE FOR GENERATING POWER AND THE METHOD THEREOF

## FIELD OF THE INVENTION

5 The present invention relates to a system for green power generation using Multi-Stage Diffusion Dialysis (MSDD), and in particular, to a system and a method using brine and fresh water being passed alternatively into a series of tanks having a plurality of chambers, where anion exchange membranes (AEM) and cation exchange membranes CEM) are placed in a designed manner to create potential energy difference between chambers within the tank to  
10 generate power and to reduce the resistance of the electrical circuit by adding electrodes and ion exchange resin.

## BACKGROUND OF THE INVENTION

In today's world, there is a continued demand for both energy and clean water. There are still regions where people lack access to a power grid and clean water. For developed countries,  
15 pollution and ever-increasing populations stress the need to expand the production of these two essential commodities. Therefore, much effort has been made globally in this aspect. The Reverse Electro Dialysis (RED) Power Generation System is one such method. In 2013, a RED system was implemented in a pilot plant on the Afsluitdijk dike in The Netherlands.

US Patent No. 4171409 by Professor Sidney Loeb discloses a 4 – step method of generating  
20 power. There are numerous patents being granted around the world related to this technology, for instance, US Patent Publication No. 20080230376, CN102610835, WO 2011050473, WO201480188. In essence, they preserve the same formation and concept as that disclosed within the disclosure of US Patent No. 4171409 with some changes in material and sequence.

The current RED system first places cation exchange membranes and anion exchange  
25 membranes alternatively in a tank to create membrane chambers, as shown in FIG. 1. Then, brine and fresh water also flow into the membrane chambers alternatively so that brine can diffuse with fresh water. This causes sodium ions to flow in the direction of the cathode and chlorine ions to flow towards the anode. One pair of cathode and anode is placed at each end of the whole membrane stack to close the electric circuit, thereby generating power.

30 The process is the reverse of the Electro Dialysis of seawater used in salt manufacturing (refer to FIG. 2 (Prior Art)). In this case, an energy source is provided to drive the flow of the ions.

There are limitations and shortcomings of the existing RED system, such as:

(1) It generates energy by tapping on the entropy change that occurs when mixing brine and fresh water. Other electrochemical potential sources such as the pH and Oxidation-Reduction Potential (ORP) of  $\text{Na}^+$  and  $\text{Cl}^-$  ions are not utilized.  $\text{NaCl}$  is partially used as a power generator and conductor, with some of its energy lost as heat energy.

5 (2) Reaction occurs only at the electrodes placed at each end. At intermediate fresh water chambers, the  $\text{Na}^+$  and  $\text{Cl}^-$  ions that flow in from each side will neutralize each other and generate heat loss.

(3) A high concentration difference is required for the current system (for example a ratio of 10:1). Lower levels of concentration difference will cause the electricity generation to be  
10 uneconomical. At the process end stage, the concentration difference is still relatively high. The chemical energy of brine is not fully utilized.

(4) Substantial amount of fresh water can be used to maintain the high concentration ratio by lowering the concentration of fresh water. This increases the freshwater resistivity and also the overall stack resistance. Theoretically, the current RED system can generate 20 watts/m<sup>2</sup>  
15 of membrane. The actual amount generated, however ranges between 1 to 3 watts/m<sup>2</sup> of membrane.

Another means to maintain the high concentration will be to have high brine concentration. However, additional processing steps will be needed before the RED process to achieve this, resulting in higher cost.

20 In summary, large amounts of freshwater with low resistance and a high concentration of brine are required by the current system due to the tight control range to achieve the optimal Brine concentration (CB)/ Freshwater concentration (CF) value.

(5) It also faces the issue of having a long electron travel distance at the internal circuit. Due to the position of the electrodes at both ends, electrons must pass through multiple  
25 chambers of pH neutral solutions which have high resistance and multiple layers of membranes.

The ion within a chamber is hydrated with water molecule. In order to travel in the body of a membrane or an electrode metal, it has to be dehydrated and then absorbed onto the surface of the membrane or electrode metal. On the other side of the membrane or electrode metal,  
30 it has to desorb and get hydrated with water molecules again before it can continue its journey in the solution. These processes of dehydration, absorption, desorption and hydration result in heat loss. Therefore, the longer the circuit, the more losses there are.

(6) There are geographical limitations in implementation the RED process due to the large amounts of freshwater required. For example, the Netherlands enjoys abundant access to both sea water and fresh water due to natural rivers available to them. However, certain regions and countries like Singapore have no natural water source, which makes application difficult.

(7) Also, the current RED method is costly to setup. The method requires many layers of costly membranes and large amounts of physical space.

(8) It requires special electrodes and electrolytes at the anolyte and catholyte chamber. The electrodes are typically required to be swapped between each end on a regular basis. The special electrolytes require regular replenishment or replacements. These requirements contribute to higher setup and operational costs. This information can be found in Bulletin of the Society of Sea Water Science, Japan. 2012, Vol. 66 (Mitsuru Higa, Shoyu Fujii and Naoki Okagawa).

(9) In terms of operational costs, the current RED method requires large amounts of pumping due to the large amount of freshwater required. Also, equipment with multiple layers of membranes runs a high risk of fouling. Coupled with the low efficiency of the power generation, the cost per unit power generated is high.

## **SUMMARY OF THE INVENTION**

The present invention provides a Multi-Stage Diffusion Dialysis (MSDD) system wherein the voltage generated is higher than that of currently available RED system, but the resistance is lower than that of current RED system.

The main object of the present invention is to provide a Diffusion Dialysis power generation system, separating ions to create an ion imbalance, allowing utilization of its potential difference, wherein Na ion abundant chamber and Cl ion abundant chamber will be formed.

The potential difference between the chambers will be generated. There is more utilization of both brine and fresh water solutions before discharge, resulting in higher power generated of the present invention.

Yet another object of the present invention is to have ion exchange resin in the ion exchange membrane chamber. Its presence serves multiple functions. In the membrane chamber, it occupies space, thereby displacing the solution and reduces the availability of space for the solution. This helps to increase contact between the solution and the membrane, improving diffusion efficiency and accelerating ion concentration change. Moreover, it serves as an

electrical current conductor due to its higher conductivity compared to water. Lastly, it works as a static mixer. Its presence generates turbulence in the solution flow.

Still a further object of the present invention to provide a Diffusion Dialysis power generation system, wherein much more electrodes in the chamber are employed and therefore a shorter circuit is resulted. Between the ion exchange membranes, there is ion exchange resin, which lowers the system resistivity even further. The solutions in the system are all either acidic or alkaline, which means lower resistivity. Owing to these factors, the electrical loss in the internal circuit is much smaller as compared to the known RED system. The present power generation system is able to generate energy with fewer losses. As half of the circuit is in electrode and copper wire, the system has a lower resistance.

Yet another object of the present invention is to provide a Diffusion Dialysis power generation system, wherein very high concentration brine or very low concentration fresh water is not required as the system is not heavily dependent on the concentration ratio in the chambers, and hence, the system saves cost by removing the stringent requirement for the incoming solutions.

A further object of the present invention is to provide a Diffusion Dialysis power generation system, wherein more electrodes are employed in the system but less ion exchange membranes are utilized as compared to the existing RED, and therefore the overall fabrication size is smaller and the cost of fabrication is cheaper. The components of the present invention do not need to be any special electrode and electrolyte to drive the process, as the incoming brine and fresh water serve well as electrolytes. With higher productivity, the number of membranes required and pumping requirements in accordance with the present invention are reduced. Therefore, the physical size of the equipment can be much smaller which translates to a lower initial setup cost and lower operating costs.

Another object of the present invention is to provide a Diffusion Dialysis power generation system; wherein due to the changing pH and small quantities of HClO being generated in the course of the chemical process, commonly encountered fouling issue can be overcome. Acidic fouling can be washed by alkaline and vice versa, and organic and inorganic contamination can also be removed. By swapping the inflow of brine and fresh water in each chamber, the same chamber can be changed from an acidic environment to an alkaline one, which regenerates the ion exchange resin and activate the electrodes. Thus, this translates to lower maintenance costs.

## **BRIEF DESCRIPTION OF THE DRAWINGS**

FIG. 1 shows a setup of a conventional reverse electrodialysis (RED) method in generating power, showing the use of cation exchange membrane (indicated as C) and anion exchange membrane (indicated as A) to create a chamber.

FIG. 2 shows a setup of a conventional electrodialysis (ED) of sea water during salt manufacturing, wherein an energy source is provided to drive the dialysis of the ions.

FIG. 3 shows a setup of diffusion dialysis system in accordance with the present invention, wherein a series of 4 tanks are employed and brine and fresh water are directed into the tanks.

FIG. 3A shows the potential between the brine and fresh water in accordance with the present invention, and also the intentional design of ion donating and ion receiving chambers.

FIG. 3B is a schematic view showing that resistance for the electric pathway through the membrane being much higher than the pathway through the anode/cathode pair and copper wire, therefore, current will pass through the wires and not through the membrane in accordance with the present invention.

FIG. 3C is a setup showing multi staged power generation with desalination in accordance with the present invention, wherein the initial incoming pair of solutions has concentrations of 30,000 ppm and approximately 800 ppm, and after electricity is generated, the diluted seawater can be used for desalination purposes, reducing the workload, saving the desalination cost.

FIG. 4 is a prior art, a setup showing the use of a hull cell chamber to simulate a conventional RED method.

FIG. 5 shows a setup simulating the diffusion dialysis system in accordance with the present invention, wherein negative ion abundant and positive ion abundant environment in each chamber were created respectively.

FIG. 6 is a graph showing the voltage in mV with respect to time and the solution NaCl 10%: 1% being used in an experiment. The voltage is generated by concentration only in accordance with RED.

FIG. 7 is a graph showing the voltage in mV with respect to time and the solution NaCl 10%: 1% after electrolysis at 1.5V for 15 min in the experiment. The voltage is generated by ion imbalance in accordance with the present invention.

FIG. 8 is a graph showing the resistance vs time for 1% NaCl with pH 6 and 1% NaCl after electrolysis with 10% NaCl at 1.5V, 15 min, and pH 7 in accordance with the present invention.

FIG. 9 is a graph showing the voltage in mV with respect to time and the solution CuSO<sub>4</sub> 10%:1% being used in an experiment, in comparison to the solution NaCl 10%:1% in the experiment for FIG. 6.

FIG. 10 is a graph showing the voltage in mV with respect to time and the solution CuSO<sub>4</sub> 10%: 1% after electrolysis at 1.5V for 15 min in the experiment, in comparison to the solution NaCl 10%: 1% after electrolysis at 1.5V for 15 min in the experiment for FIG 7.

## DESCRIPTION OF A PREFERRED EMBODIMENT

FIG. 1 is prior art showing a setup of a conventional reverse electrodialysis (RED) method in generating power, showing the use of cation exchange membranes(indicated as C) and anion exchange membranes (indicated as A) to create membrane chambers. In this conventional method, reverse electrodialysis (RED) of sea water is used. FIG. 2 is prior art showing a setup of the salt manufacturing process, where an energy source is provided to drive the flow of the ions.

Referring now to the drawings, especially to FIG. 3, there is shown generally a diffusion dialysis power generation system 1000 comprising a plurality of tanks including a start stack tank 100, a restore stack tank 200, activate stack tank 300, and a scavenge stack tank 400. Brine and fresh water are directed into these tanks 100, 200, 300, 400 in series to reduce polarization and the generation of reverse current in the ion travel. FIG. 3 shows schematically the arrangement setup of the power generation system of the MSDD system in accordance with the present invention. In the figure, arrow next to letter B indicates the flow of brine, and arrow next to letter F indicates the flow of fresh water. The tanks are positioned in a way such that the flow of brine and fresh water between the tanks is gravity-driven.

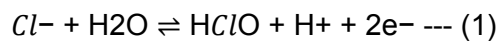
Solution near the surface of ion exchange membrane is diffused or is ready to diffuse. Solution at the centre of the chamber has to travel by electrophoresis to the surface of an ion exchange membrane before it can diffuse. Therefore, electrophoresis becomes the critical path of the diffusion. The ion exchange resin (A) serves as a spacer in the brine chamber reducing the brine volume in the chamber so that the majority of the brine is kept in contact with the membrane. The ion exchange resin in the fresh water chamber serves as an ion accommodation other than as a spacer.

The ion exchange resin also serves as a mixer as its presence generates turbulence in the solution flow. This helps the majority of the solution to become involved in the diffusion process thereby enhancing the generation of ion imbalance.

As show in the figure, the Start Stack 100 consists of anion exchange membranes (AEM) 101, AEM chamber for brine 102, AEM chamber for freshwater 103, cathode at brine chamber 104 and anode at freshwater chamber 105. Only Cl ions can pass through AEM101. The flow of the ions generates current. The whole circuit is closed by the connection of an outside wire (not shown).

In AEM for brine 102 chamber, Cl ions at the brine chamber will flow to the fresh water chamber due to concentration difference. Na ions at the brine chamber remain. The AEM chamber for freshwater 103 has an anode 105 which attracts Cl ion only. The AEM chamber for freshwater 103 forms a negative charge abundant environment. The environment is unstable and hungers for positive charge. The excess negative charge will gather at the tip of the anode 105 and will be released similar to a lightning conductor. Referring to Equation 1 below, the negative charge then releases electrons and travel to cathode 104 in AEM chambers for brine 102 through a copper wire (not shown). As a result, an electric current is formed.

From equation 1 below, the Cl ions in brine or in fresh water reacts with water to form hypochlorite, HClO, which is an effective agent to kill off bacteria and prevent fouling from occurring at the membranes.

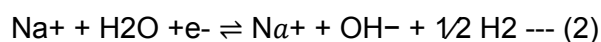


The potential generated from this reaction can be -1.49V if there is free Cl<sup>-</sup> activity at 1 normality concentration.

Thus, the freshwater flow becomes acidic with small amounts of HClO.

The AEM chamber for brine 102 will have more Na ions than Cl ions, forming a positive ion abundant environment. The environment is unstable and hungers for negative charge. The excess positive ion will be gathered at the tip of the cathode 104 of the AEM chamber for brine 102, which attracts electrons from the anode 105 in the adjacent AEM chambers for freshwater 103. The excess Na<sup>+</sup> ions will also hydrolyse with water to cause the AEM chamber for brine 102 to become alkaline.

Referring to the equation (2) below:



On the left side of equation 2, the sodium ion (Na<sup>+</sup>) is too active to be reduced. The positive charge gathered at the cathode attracts electron (e<sup>-</sup>) from the freshwater chamber 103 via the

external electrical circuit. The water molecule ( $\text{H}_2\text{O}$ ) acts as an oxidizer and reduces itself into  $\text{OH}^-$  ions (thereby causing alkalinity) and hydrogen ( $\frac{1}{2} \text{H}_2$ ).

The potential generated via this reaction can be  $-0.828\text{V}$  if there is free  $\text{Na}^+$  activity at 1 normality concentration. However, it is unlikely to reach this potential due to losses in reverse current. It is also preferable not to reach that level of potential as at  $-0.828\text{V}$ , hydrogen gas will be generated and emitted. The electron will be used up in the formation of hydrogen gas and lost to the surroundings rather than being used for power generation.

The Restore Stack 200 consists of cation exchange membranes (CEM). It is supposed to restore the ions from an imbalanced state to a balanced state. Only Na ions can pass through CEM. The CEM chamber for freshwater 203 receives the freshwater flowing from the AEM chamber for freshwater 103, which only has Cl ions. This will results in a craving for Na ions from neighbouring AEM chambers for brine 102. The flow of ions results in current generation. By the end of the stack, the amount of Na ions equalizes the amount of Cl ions in every flow. However, there is still significant difference in concentration between the brine and freshwater flows. The brine and fresh water will be pumped back to the separate elevated reservoir tower.

In the Activate Stack 300, brine flows into AEM chambers 307, 303, CEM chamber 308 and 305, while freshwater flows into chambers 304, 309 and 306.

In chamber 303 of the Activate Stack tank 300, only Cl ions pass through AEM 301 and go to chamber 304 and 309 (or known as ion receiver chamber), leaving behind Na ions. Chamber 303 becomes rich in Na ions, wherein positive charges will gather at cathode 310 and attract electrons from anode 312 located at chamber 305 through the external electrical circuit.

In chamber 305, only Na ions pass through CEM 302 and go to chamber 306 and 309, leaving behind Cl ions. Chamber 305 becomes rich in Cl ions, wherein negative charges will gather at anode 312 and release electrons to cathode 310 at chamber 303 through the external electrical circuit.

Chamber 304 receives only Cl ions from brine chamber 303 and 307 (ion donating chamber), due to AEM 301. Chamber 304 becomes Cl ion rich, wherein negative charges build up and release electrons from anode 311 to cathode 313 at chamber 306 through the external circuit.

Chamber 306 receives only Na ions come from brine chamber 305 and 308 (ion donating chamber), due to CEM 302. Chamber 306 becomes Na ion rich, wherein positive charges build up and attract electrons from anode 311 at chamber 304 through the external circuit.

In Scavenge Stack 400, Chamber 404 receives the acidic, Cl ion rich freshwater flow from chamber 304. The excess Cl ions attract the excess Na ions from the neighbouring brine chambers 403 and 407. The excess Cl ion will be equalized by excess Na ions, to the point where the quantities of Na and Cl are the same. The ionic flow between the chambers becomes the current.

Chamber 403 receives alkaline, Na ion rich brine chamber 303. The excess Na ions pass through CEM 401 to enter neighbouring freshwater chamber 409 (ion receiving chamber). The excess Na ion is therefore reduced to the point where the quantities of Na and Cl are the same. The ionic flow between the chambers becomes the current.

Chamber 405 receives the acidic, Cl ion rich freshwater flow from chamber 305. The excess Cl ions pass through AEM 402 to enter neighbouring freshwater chamber 409 (ion receiving chamber). The excess Cl ion is therefore reduced to the point where the quantities of Na and Cl are the same. The ionic flow between the chambers becomes the current.

Chamber 406 receives alkaline, Na ion rich brine from chamber 306. The excess Na ions attract the excess Cl ions from the neighbouring brine chamber 405 and 408. The excess Na ion will be equalized by excess Cl ions, to the point where the quantities of Na and Cl are the same. The ionic flow between the chambers becomes the current.

By adding up the potential generated from equations (1) and (2), the possible potential generated can be:

$$-0.828 + (-1.49) = -2.318 \text{ V} \text{ --- (3)}$$

Assuming a 50% loss in ion concentration, the potential shall be

$$-2.318 \div 2 = -1.159 \text{ V} \text{ --- (4)}$$

The Nernst equation can be used to calculate the potential difference  $\Delta E$  between brine and fresh water in the following equation:

$$\Delta E = \frac{RT}{F} (t_{\text{Na}} \log \frac{a_{\text{NaB}}}{a_{\text{NaF}}} - t_{\text{Cl}} \log \frac{a_{\text{ClB}}}{a_{\text{ClF}}})$$

$\Delta E$  : potential difference between brine and fresh water

RT: Universal gas constant and temperature in Kelvins

F: Faraday constant

tNa: Na<sup>+</sup> transport number

tCl: Cl<sup>-</sup> transport number

aNaB: Na<sup>+</sup> in brine activity

aNaF: Na<sup>+</sup> in fresh water activity

5 aClB: Cl<sup>-</sup> in brine activity

aClF: Cl<sup>-</sup> in fresh water activity

As described earlier, the setup generates either a positive charge abundant or a negative charge abundant environment. In a positive charge abundant environment, Na<sup>+</sup> activity becomes higher compared to Cl<sup>-</sup> activity, and vice versa in a negative charge abundant environment.

10

Referring to chamber 102 and 103 in Fig 3,

aNaB/aNaF will be very large as  $a_{NaB} \gg a_{NaF}$  (As aNaF is very small in fresh water chamber)

aClB/aClF will be very small as  $a_{ClF} > a_{ClB}$  (aClB is small due to  $a_{NaB} > a_{ClB}$  in brine chamber in alkaline condition. aClF is large due to  $a_{ClF} \gg a_{NaF}$ )

15

The Nernst Equation can also be used to calculate the potential generated in a RED system.

$$E = (t_+ + t_-)(RT/F) \ln(CB/CF) \text{ --- (5)}$$

wherein

- 5 E: Potential in V.
- t<sub>+</sub>, t<sub>-</sub>: Cation/Anion transport number
- R: Universal gas constant
- T: Temperature in Kelvins
- F: Faraday constant
- 10 CB: Brine concentration
- CF: Fresh water concentration

Assuming a current RED process with a 10:1 ratio at room temperature (298K) is in operation,

$$\text{Half cell } E = (0.4 + 0.6) (8.314)(298)/(96485.33) \ln(10) = 0.06V \text{-----(6)}$$

- 15 t<sub>+</sub> is typically 0.4, t<sub>-</sub> is typically 0.6.

Multiply by 2 due to the presence of two half cells.

$$0.060 \text{ V} \times 2 = 0.120V \text{ --- (7)}$$

In absolute values, the potential generated in equation (4) is still larger than that in equation (7), 1.159V > 0.120V.

- 20 From the Nernst Equation, we can see that the ratio of brine concentration to fresh water concentration impacts greatly the amount of potential generated. To maintain a high CB/CF, large amounts of fresh water is needed to keep CF low.

On the other hand, the CF should be moderately high to reduce fresh water resistivity. The below equation is used to calculate the Stack resistance, which is the total resistance of the entire setup.

25

$$R_{\text{stack}} = R_{\text{el}} + N(R_B + R_F + R_{\text{CEM}} + R_{\text{AEM}})/S \text{ --- (8)}$$

wherein

- R<sub>stack</sub>: Stack resistance
- R<sub>el</sub>: Electrode resistance
- 30 N: Number of membrane pair
- S: Membrane surface area

RB: Resistance of brine  
 RF: Resistance of freshwater  
 RCEM: Cation exchange membrane resistance  
 RAEM: Anion exchange membrane resistance

5

When there is a large amount of fresh water, then the fresh water concentration is small. This means that resistance of freshwater, RF will be large. As RF contributes significantly to the overall stack resistance compared to RB (resistance of brine), a large RF will result in a large Rstack. In addition, the pH values of freshwater and brine remains at 7 neutral, as the balance of Na<sup>+</sup> and Cl<sup>-</sup> ions is maintained. This causes a lack of free electrons and therefore the RF and RB values to be high. The high overall resistance therefore has a negative impact on the amount of potential generated.

10

$$\text{Power} = IE = (E/R).E = E^2/R = ((t^+ + t^-)(RT/F) \ln (C_B/C_F))^2/(R_{\text{stack}}) \text{ --- (9)}$$

15

For power generation using reverse electrodialysis method, the low conductivity of fresh water has always been a major obstacle to its efficiency and effectiveness. In accordance with the preferred embodiment of the present invention, the fresh water is mostly kept either acidic or alkaline. As a result, conductivity is always higher than that of the conventional RED methods.

Referring now to the drawings, especially to FIG. 3A, another unique design of the MSDD is the addition of ion donating or receiver chambers to overcome low ion diffusion rates.

20

A critical bottleneck in the present invention is the ion diffusion rate between the brine and freshwater streams. When the concentration difference between freshwater and brine drops, the ion diffusion rate will decrease. This delays the creation of the highly electron rich or highly electron deficient environment in their respective chambers, thereby negatively affecting the current or electromotive force generated.

25

Therefore, in the activate stack and the scavenge stack, where the concentration difference is lower due to having undergone the start stack and restore stack, ion donating chambers and ion receiving chambers are intentionally placed. These chambers increase the ion diffusion rate and hasten the creation of highly negative ion rich or highly positive ion rich environment. Due to the balanced state of the ions in these chambers, there is no potential difference generated, and therefore no electrodes installed.

30

Another bottleneck is the electrical resistance of the internal circuit. Freshwater, that has balanced amounts of Na and Cl, possesses high electrical resistance. By placing electrodes as shown in the FIG. 3B, the high resistance of the freshwater stream can be bypassed. Ion

exchange resin also helps to lower the resistance. The ion exchange resin acts as a quick conductor in the circuit, replaces the water space in chamber, serves as an agitator or static mixer, and an ion concentration stabiliser.

In the present invention, in the fresh water chamber at activate tank and scavenger tank, the Na ion and Cl ion from the adjacent brine chamber are attracted to each other, and when there are more Cl ions than Na ions in the brine chamber, the brine is directed to the brine chamber of AEM stack tank, and wherein the Cl<sup>-</sup> ions will pass through AEMs, and Na<sup>+</sup> ion remains and forms positive charge abundant, and the positive charge gather at the tip of the cathode attracts electrons from the adjacent fresh water chamber through the copper wire and the anode, resulting in an electric current flow.

FIG. 3C is a setup showing multi staged power generation with desalination in accordance with the present invention, wherein the initial incoming pair of solutions has concentrations of 30,000 ppm and approximately 800 ppm, and after electricity is generated, the diluted seawater can be used for desalination purposes, reducing the workload, saving the desalination cost.

The present invention provides a method of power generation using multi-stage diffusion dialysis comprising the step of :

(a) directing brine and fresh water into a series of 4 tanks including a start stack tank, a restore stack tank, an activate stack tank and a scavenge stack tank:

(b) causing the brine in start stack tank to flow into chamber with AEM;

(c) causing the fresh water in start stack tank to flow into chambers located between the brine chambers;

(d) driving Cl<sup>-</sup> ions in the brine chambers with AEM on both sides to pass to the adjacent fresh water chamber; and remaining Na<sup>+</sup> ions in the brine chamber to form a positive charge abundant environment;

(e) driving Na ions in the brine chambers with CEM to pass to the fresh water chamber, and forming a negative charge abundant environment of Cl<sup>-</sup> ions at the brine chamber; and

(f) releasing electrons from the negative charge and travelling through the anode at the fresh water chamber, and the copper wire towards the cathode to form electric current.

In the method, in the fresh water chamber, ion receiving chamber, the Na<sup>+</sup> ion and the Cl<sup>-</sup> ions attract each other, and the anode receives electrons from the solution and the electrons flow from the anode via copper wire to cathode at the brine chamber.

Other advantages as compared to the current RED power generation method include:

- 5 Electrical loss due to electron travel distance and resistance in the internal circuit is much less. Also, the method in accordance with the present invention does not require a high concentration difference between the brine and freshwater streams, thus making the method more versatile.

## WORKING EXAMPLES

### 10 Experiment Method and Data

#### Experiment 1

The purpose of Experiment 1 is to confirm the higher potential that will be generated by the present Multi-Stage Diffusion Dialysis method compared to the convention RED method.

- 15 Referring to FIG. 4, there is shown a setup of chamber to simulate voltage obtained by convention RED method. This experiment is to confirm the higher potential that will be generated by the Multi-Stage Diffusion Dialysis of the present method as compared to the convention RED method. A hull cell chamber is used and the partition is made of polypropylene cloth. As there is less highly concentrated RO effluent brine and relatively more sewage water, the volume of 10% NaCl solution is lower than that of the 1% NaCl solution.
- 20 The solutions are poured into their respective chambers, and the potential generated is then measured.

Table 1 – Voltage of Na-Cl balanced 1% NaCl solution/10% NaCl solution

|              |       |      |      |      |      |      |      |      |
|--------------|-------|------|------|------|------|------|------|------|
| Time (min)   | 1     | 2    | 3    | 4    | 5    | 6    | 7    | 8    |
| Voltage (mv) | 100.3 | 92.0 | 89.5 | 87.5 | 87.1 | 86.3 | 85.3 | 83.3 |

25

FIG. 6 is a graph showing the voltage generated within a specific period of time.

As seen earlier in equation (6), the theoretical potential generated by the convention RED method is:

$$E = (t_+ + t_-) (RT/F) \ln(C_B/C_F) = 0.06V$$

Multiply by 2 due to two half cells.

$$\approx 2 \times 0.06 = 0.12 \text{ V --- (9)}$$

Figure 5 shows an arrangement of power generation where more fresh water and less RO effluent brine. In this setup, Ti electrodes coated with IrO<sub>2</sub> are used.

5 The setup in FIG. 5 simulates the Diffusion Dialysis method of the present invention. In this setup, a Cl ion abundant and a Na ion abundant environment in each chamber respectively are created. The concentration factor of 10:1 in FIG. 4 setup is maintained. After pouring each solution into their respective chamber 52, 53, a rectifier 51 at 1.5V setting and negligible current is used to electrolyze both solutions for 15 minutes to generate the Cl ion abundant and Na ion abundant environment. This is done as PP cloth as a partition 54 does not have selectivity and therefore unable to generate the Cl ion abundant and Na ion abundant environment on its own. The low voltage setting is to prevent chlorine gas from emitted, which will give a false potential difference reading. After electrolysis, the potential generated is measured.

15 Table 2 – Voltage of Cl rich 1% NaCl solution/ Na rich 10% NaCl solution

|              |     |     |     |     |     |     |     |
|--------------|-----|-----|-----|-----|-----|-----|-----|
| Time (min)   | 1   | 2   | 3   | 4   | 5   | 6   | 7   |
| Voltage (mv) | 940 | 900 | 868 | 843 | 822 | 803 | 786 |

From Equation 3, the theoretical potential generated should be  $-0.828 + (-1.49) = -2.318\text{V} = 2318 \text{ mV}$  at 1 normality concentration. The lower than theoretical potential measured in the experiment is due to low Cl activity.

FIG. 7 is a graph showing the voltage generated against time in accordance with the present invention. From the graph, the initial reading of 940mV is lower than the theoretical value ( $-0.828 + (-1.49) = -2.318\text{V} = 2318\text{mV}$ ), but it is still much higher than the theoretical 120mV of the conventional RED method.

25 From the results, it indicates that the electrolyzed solution, which simulated the Multi-Stage Diffusion Dialysis method of the present invention, is able to generate a higher potential than the non-electrolyzed solution, which simulated the conventional RED method.

## Experiment 2

In accordance with the preferred embodiment of the present invention, the purpose of Experiment 2 is to confirm the lower internal circuit resistance of the Multi-Stage Diffusion Dialysis method compared to the convention RED method.

The setups for both methods are the same as that of Experiment 1. A multimeter is used to measure the resistance of the solution at the low concentration chamber at a distance of approximately 1cm. The electrode used is titanium coated with iridium oxide. The surface area is 20 cm<sup>2</sup>.

5 Table 3 –Resistance of Na-Cl balanced 1% Na-Cl solution

|                 |       |      |      |      |       |
|-----------------|-------|------|------|------|-------|
| Time (min)      | 1     | 2    | 3    | 4    | 5     |
| Resistance (kΩ) | 1.134 | 1.88 | 2.55 | 3.11 | 3.779 |

Table 4 – Resistance of Cl rich 1% NaCl solution

|                 |       |      |       |       |       |
|-----------------|-------|------|-------|-------|-------|
| 10 Time (min)   | 1     | 2    | 3     | 4     | 5     |
| Resistance (kΩ) | 0.462 | 0.73 | 0.971 | 1.281 | 1.521 |

FIG. 8 is a graph showing the resistance of 1% NaCl (as it is pH 7) and the resistance of 1% NaCl after electrolysis with 10% NaCl at 1.5V, 15 min, pH ~6.

From the results, it can be concluded that the electrolyzed solution, pH is 6, which simulated the Multi-Stage Diffusion Dialysis method of the present invention, has lower resistance compared to the non-electrolyzed solution, which pH is 7, which represents the conventional RED method.

### Experiment 3

20 The purpose of Experiment 3 is to confirm that the electro potential energy of Na and Cl is truly harnessed.

The setup is the same as that of Experiment 1, but replaced with unhydrated 1% copper sulfate (CuSO<sub>4</sub>) solution and 10% copper sulfate solution. First, we measure the potential generated as per Setup A.

Table 5 - Voltage of Cu-SO<sub>4</sub> balanced 1% CuSO<sub>4</sub> solution

|               |       |       |       |       |      |
|---------------|-------|-------|-------|-------|------|
| 25 Time (min) | 1     | 2     | 3     | 4     | 5    |
| Voltage (mv)  | 114.0 | 109.2 | 105.5 | 102.2 | 98.9 |

Referring to FIG. 9 and 10, it is observed that both values range at around 100mV and then slowly declines. This shows that regardless of the salt in the solution, the amount of potential generated by two solutions with a concentration factor of 10:1 is the same.

The experiment is then repeated as per setup in FIG. 5, which electrolysis is performed to create SO<sub>4</sub> ion abundant and Cu abundant environments.

Table 6 – Voltage of SO<sub>4</sub>-2 rich 1% CuSO<sub>4</sub> solution/Cu rich 10% CuSO<sub>4</sub> solution

|              |     |     |     |     |     |
|--------------|-----|-----|-----|-----|-----|
| Time (min)   | 1   | 2   | 3   | 4   | 5   |
| Voltage (mv) | 682 | 656 | 633 | 614 | 596 |

Comparing the results between Table 6 and Table 2, it indicates that for both cases, the potential generated is higher than their respective results from setup in FIG. 4. However, referring to FIG. 9 & 10, the potential generated by the NaCl solution in Experiment 1 is higher than that of the CuSO<sub>4</sub> solution in this experiment. By referring to the Table of Standard Electrode Potential, it can be seen that the difference between Na and Cl is much higher than between Cu and SO<sub>4</sub>.

Before the CuSO<sub>4</sub> experiment, a preliminary qualitative experiment was conducted. NiCl<sub>2</sub> was used. 1% and 10% NiCl<sub>2</sub> were electrolysed under 5 V 1A 5 minutes. Slight bubble was observed in anode. After electrolysis, 1400mV was measured. The same condition electrolysis was conducted with NaCl, 1900mV was measured. The potential difference between Na and Cl is higher than Ni and Cl. Both NiCl<sub>2</sub> and NaCl share a common basis in Cl being the negative ion. The difference in voltage generated comes from the difference in potential between Ni and Na, with Na possessing higher potential.

Therefore, with these experiments, it is concluded that the Multi-Stage Diffusion Dialysis method of the present invention does truly utilize the electro potential energy of the ions to perform power generation.

The foregoing description is intended primarily for purposes of illustration. This invention may be embodied in other forms or carded out in other ways without departing from the spirit or scope of the invention. Modifications and variations still falling within the spirit or the scope of the invention will be readily apparent to those of skill in the art.

**CLAIMS**

1. A multi-stage diffusion dialysis (MSDD) system for power generation using brine and fresh water comprising
  - (a) a series of at least 4 stack tanks including a start stack tank to create ion imbalance, a restore stack tank to restore ion balance, an activate stack tank and a scavenge stack tank;
  - (b) a plurality of chambers within each of the four stack tanks, wherein the chambers contain either brine solution or fresh water, and the chambers are created by partitioning the stack tanks with ion exchange membranes; and
  - (c) a pair of cathode and anode for each pair of chambers within the stack tanks, wherein when there is an excess of sodium ions in a chamber due to either outward diffusion of  $\text{Cl}^-$  ions to, or inward diffusion of  $\text{Na}^+$  from, neighbouring chambers, the excess sodium ions will gather at the cathode and attract electron at the adjacent chamber through the anode, or wherein when there is an environment of excess chlorine ions due to either outward diffusion of  $\text{Na}^+$  ions to, or inward diffusion of  $\text{Cl}^-$  ions from, neighbouring chambers will cause  $\text{Cl}^-$  to gather at the anode and release electrons, and an external circuit thereby the flowing of electron will result from the potential difference between  $\text{Na}^+$  and  $\text{Cl}^-$  being tapped to generate an electrical potential and an electrical current is created.
2. The multi-stage diffusion dialysis system for power generation as set forth in Claim 1, wherein brine and fresh water are directed into the start stack tank, the restore stack tank, the activate stack tank and the scavenge stack tank.
3. The multi-stage diffusion dialysis system for power generation as set forth in Claim 1, wherein when brine flows into chambers with anion exchange membranes (AEMs) on both sides, only  $\text{Cl}^-$  ions diffuse to adjacent fresh water chamber and remaining  $\text{Na}^+$  ion in the chamber forming  $\text{Na}^+$  ion greater than  $\text{Cl}^-$  ion imbalance environment.
4. The multi-stage diffusion dialysis system for power generation as set forth in Claim 1, wherein the fresh water flows into the chambers that are positioned between the two anion exchange membranes (AEMs), and only  $\text{Cl}^-$  ions diffuse into the chamber forming  $\text{Cl}^-$  ion greater than  $\text{Na}^+$  ion imbalance environment.
5. The multi-stage diffusion dialysis system for power generation as set forth in Claim 1, wherein when brine flows into chambers with cation exchange membranes (CEMs) on both sides, and only  $\text{Na}^+$  ions diffuse into fresh water chamber resulting  $\text{Cl}^-$  ion remains forming  $\text{Cl}^-$  ion greater than  $\text{Na}^+$  ion imbalance environment.

6. The multi-stage diffusion dialysis system for power generation as set forth in Claim 1, wherein the fresh water flows into the chambers that are positioned between the two cation exchange membranes (CEMs), and only Na ions diffuse into the chamber forming Na ion greater than Cl ion imbalance environment.
- 5 7. The multi-stage diffusion dialysis system for power generation as set forth in Claim 1, wherein the chambers are mounted with electrode and/or without electrode.
8. The multi-stage diffusion dialysis system for power generation as set forth in Claim 1, wherein in the fresh water chamber where there is anion exchange membrane (AEM) on one side and cation exchange membrane (CEM) on the other side at activate tank and scavenger tank, the Na ion and Cl ion from the adjacent brine chamber are attracted to each other.
- 10 9. The multi-stage diffusion dialysis system for power generation as set forth in Claim 1, wherein
  - (a) there are excess Na<sup>+</sup> ions, thus forming a positive charge abundant environment, and the positive charges gather at the tip of the cathode and attract electrons from the adjacent chamber through a copper wire and the anode, resulting in an electric current flow;
  - (b) there are excess Cl<sup>-</sup> ions, thus forming a negative charge abundant environment, and the negative charges gather at the tip of the anode and release electrons to the adjacent chamber through a copper wire and the cathode, resulting in an electric current flow.
- 20 10. The multi-stage diffusion dialysis system for power generation as set forth in Claim 9, wherein the positive charge abundant brine is directed to the scavenger stack tank, and the excess Na<sup>+</sup> ion is passed through the cation exchange membranes (CEMS) and go into the adjacent fresh water chambers.
- 25 11. The multi-stage diffusion dialysis system for power generation as set forth in Claim 1, wherein an ion donating chamber is a brine chamber enclosed by anion exchange membrane (AEM) and cation exchange membrane (CEM), and an ion receiving chamber is a fresh water chamber enclosed by anion exchange membrane (AEM) and cation exchange membrane (CEM), and both of the chambers are in ion balanced condition, and wherein the ion donating and the ion receiving chamber are placed to overcome low ion diffusion rate, in order to efficiently create an imbalanced state in the ion concentration of the neighbouring chambers.
- 30

12. A method of power generation using multi-stage diffusion dialysis system comprising the step of :

(a) directing brine and fresh water into a series of 4 tanks having a plurality of chambers, including a start stack tank, a restore stack tank, an activate stack tank and a scavenge stack tank, wherein a pair of cathode and anode for each pair of chambers within the stack tanks:

(b) causing the fresh water in start stack tank to flow into chambers located between the brine chambers;

(c) driving  $\text{Cl}^-$  ions in the brine chambers with anion exchange membrane (AEM) on both sides to pass to the adjacent fresh water chamber; and remaining  $\text{Na}^+$  ions in the brine chamber to form a positive charge abundant environment; and

(d) forming a circuit by attracting electrons from the negative charge and travelling through the anode at the fresh water chamber, and a copper wire towards the cathode to form electric current.

13. The method of power generation of Claim 12, wherein in the fresh water chamber, ion receiving chamber, the  $\text{Na}^+$  ion and the  $\text{Cl}^-$  ions attract each other.

14. The method of power generation of Claim 12 wherein the ion exchange resin acts as a quick conductor in the circuit, replaces the water space in the chamber, serves as an agitator or static mixer, and an ion concentration stabiliser, and wherein the electrodes in the chambers have reduced circuit resistance of the system.

15. The method of power generation of Claim 12, wherein the brine chamber, excess  $\text{Na}^+$  ion pass through the cation exchange membranes (CEMs) to the fresh water chamber, which generating a positive charge abundant environment in the fresh water chambers.

16. The method of power generation of Claim 12, wherein the ion donating chamber and ion receiving chamber being intentionally designed are used to promote an imbalance of ions, which causes potential difference.

17. The method of power generation of Claim 12, wherein  $\text{HClO}$  is generated in the  $\text{Cl}^-$  ion rich environments, which prevents membrane fouling at the membranes.

18. The method of power generation of Claim 12, wherein the electrochemical potential energy difference between these separated Na and Cl ions is being tapped on to generate power.