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Process of desalination of low energy consumption. Energy + magnetohydrodynamics (E + MHD) desalination process

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ABSTRACT

This paper shows the theoretical justification of a new process of desalination which involves the use of electrodialysis concepts regarding the use of charged- ion selective membranes to create differentiated cells of concentrated salt water and diluted or desalinated water. However, the concept of transporting ions changes in this case with respect to electrodialysis, since in order to transform the ions, the second term of the Lorentz equation is used instead of the first term. In the first term, there is an electric field, which is used by conventional electrodialysis, whereas in the second term there is the joint action of a magnetic field together with the velocity of the fluid to cause the motion of electric charges according to their signs. The use of a magnetic field instead of the use of an electric field can be an advantage when trying to solve the electro-neutrality of the cells of the edges without having to turn to the use of redox reactions. The expected energy saving is more than 75% in the case of electrodialysis energy consumption and more than 45% in the case of reverse osmosis energy consumption. This process of desalination works from two main parameters: 1) One permanent magnetic dipole. Therefore the energy of this magnetic field remains inalterable throughout the time; 2) The electric charge speed on the desalted water vs. the magnetic field of the magnetic dipole. This speed does not have to be high.

Keywords: Desalination; Magnetic, field, Electrodynamics; Ion exchange membrane, Energy, Magnetohydrodynamics; Reverse osmosis

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1. Introduction

This paper makes the case that models the energy behaviour of the E + MHD (energy + magnetohydrodynamics) desalination process.

1. Introduction to key concepts used during exposure.
2. Theoretical minimum power required for desalination by E + MHD.
3. Minimum correction consumption according to the equations of magnetohydrodynamics.
4. Energy losses by thermodynamic irreversibilities.
5. Total real energy consumption of the E + MHD desalination process.

1.1. Ion exchange process

The E+MHD desalination process is a process of ion exchange that uses selective membranes. The same membranes are used in conventional electrodialysis. The difference of E + MHD with respect to electrodialysis is the energy consumption behaviour.

Electrodialysis (Fig. 1) is a desalination method based on selective membranes of positive or negative ions [1]. The electrodes are at the edges of the stacks of cells. One

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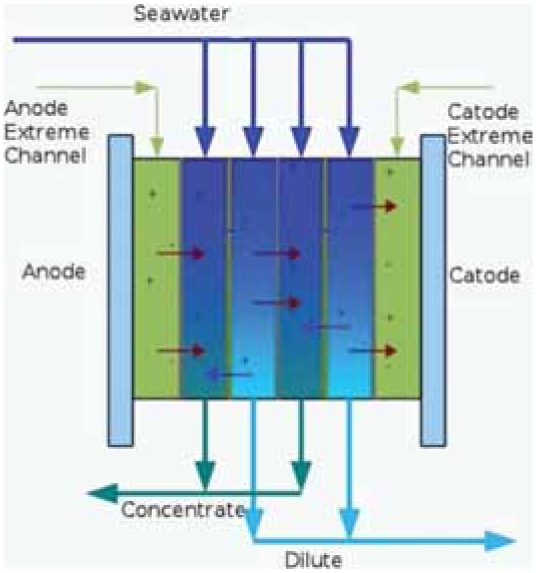

Fig. 1. Diagram of the electrodialysis desalination method.

acts as a cathode and the other as anode. The role of these electrodes is to create an electric field. The electric field causes differently charged ions to be attracted in a different sense. The figure shows cations being attracted to the left and anions being attracted to the right.

On the way towards electrodes, ions pass through a type of membrane but are prevented from further migration by other membranes and therefore remain in there. With the geometrical configuration of the figure, the different cells tend to differentiate in cells where the ion concentration decreases and cells where the ion concentration increases.

In this way, desalination of part of the water that gets into the system is obtained. Up to here, it has been explained what is normally known as electrodialysis (ED), but it is necessary to go deeply into this subject in order to understand the true scope of the new desalination process presented here.

The electric field of the electrodes attracts ions. When ions pass through membranes, electrical potentials are created in the membranes because of two main reasons.

1. Potentials as a result of the different concentrations on both sides of the membranes.
2. Potentials as a result of the different charge concentrations in the membrane and in solution.

The first ones are evaluated using the Nernst concentration (the global equation is the Goldman equation).

$$V = V_1 - V_2 = \pm 2,3\frac{KT}{e}\log\frac{C_1}{C_2} \tag{1}$$

The second ones are determined by means of the Donnan equation

$$V = \frac{-KbT}{Z_{ie}}\cdot\ln\frac{C_{i2}}{C_{i1}} \tag{2}$$

As we can see in the formula, it is proportional to base 10 logarithm of the quotient of the concentrations on both sides of the membrane. Therefore, the greater the difference of concentrations, the greater would be the flow necessary so that ions are capable to pass through the concentrated channel from the dilute channel.

Apart from these potentials, electrodialysis must solve the exceptional case of the cells in the edges. In every electrochemical process, the condition of electroneutrality must be satisfied. In electrodialysis, it is easy to understand how this effect is produced in the inner cells. In the inner cells, for each cation that gets in or out on the left, there is an anion getting in or out on the right. In this way, the condition of electro-neutrality is satisfied in every cell. Notwithstanding, it does not happen the same with the extreme cells due to the fact that ions get in or out by only one of the sides.

With the matter at hand, this is solved by means of the oxidation- reduction process in order for the right and left cell to keep satisfying the electro-neutrality conditions.

These redox processes are a serious problem from the point of view of energy efficiency, because a great quantity of energy is consumed in two processes:

- Energy is consumed in order to provoke the redox reaction.
- Energy is consumed in order to transport electrons through the dissolution. This is even more stressed when the electrical resistance of the diluate channels increases due to the fact that the water is an electric insulator and what provides conductivity is precisely the existence of dissolved ions [2].

These two above mentioned energy consumptions are responsible for the fact that electrodialysis is a less efficient desalination process than reverse osmosis.

1.2. Lorentz force

In physics, the Lorentz force is the force on a point charge due to electromagnetic fields. It is given by the following equation in terms of the electric and magnetic fields:

$$\vec{F} = q\left(\vec{E} + \vec{v}\times\vec{B}\right) \tag{3}$$

where $\vec{F}$ is the force (N); $\vec{E}$ is the electric field (V/m); $\vec{B}$ is the magnetic field (T); q is the electric charge of the particle (C), $\vec{v}$ is the instantaneous velocity of the particle (m/s). More information can be found in [3] and [4].

1.3. Nernst potential

In electrochemistry, the Nernst equation is an equation that can be used (in conjunction with other information) to determine the equilibrium reduction potential of a half-cell in an electrochemical cell. It can also be used to determine the total voltage (electromotive force) for a full electrochemical cell.

$$E_{\text{eq,K}} = \frac{RT}{zF}\ln\frac{[\text{K}]_0}{[\text{K}]_j} \qquad (4)$$

K = K^+ (potassium cation)

where $E_{\text{eq,K}^+}$ is the equilibrium potential for potassium (V); R is the universal gas constant equal to 8.314 $\text{J}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$; T is the absolute temperature (K); z is the number of elementary charges of the ion in question involved in the reaction; F is the Faraday constant equal to 96,485 $\text{C}\cdot\text{mol}^{-1}$ or $\text{J}\cdot\text{V}^{-1}\cdot\text{mol}^{-1}$; $[\text{K}^+]_\text{o}$ is the extracellular concentration of potassium ($\text{mol}\cdot\text{m}^{-3}$ or $\text{mmol}\cdot\text{l}^{-1}[\text{K}^+]$) is the concentration of potassium.

Two solutions of potassium chloride (Fig. 2) are separated by a membrane permeable to potassium ions.

The diffusion of potassium ions from compartment 1 to compartment 2 results in an excess of negative charge in chamber 1 and an excess of positive charge in compartment 2. The diffusion of potassium ions is due to the concentration difference between the compartments. The membrane allows only potassium ions to pass.

More information about the Nernst potential is given in [5] and [6].

1.4. Magnetohydrodynamics equations

Magnetohydrodynamics (MHD) is the academic discipline which studies the dynamics of electrically conducting fluids. Examples of such fluids include plasmas, liquid metals, and salt water. More information about MHD is given in [7] and [8].

2. Minimum energy required for the E + MHD desalination process

This section exposes how the Nernst formula is used to calculate the minimum work for the E + MHD desalination process.

We imagine the following system (Fig. 3) assuming that the membranes are ideal. The system in Fig. 3 is an E + MHD system simplified with a single pair of membranes. At the outset the following requirements are fulfilled:

- The floodgates are closed and they do not allow the ion exchange.
- The ion concentration in zone A is the same as in zone B.
- The two zones meet the condition of electro-neutrality.

2.1. First stage

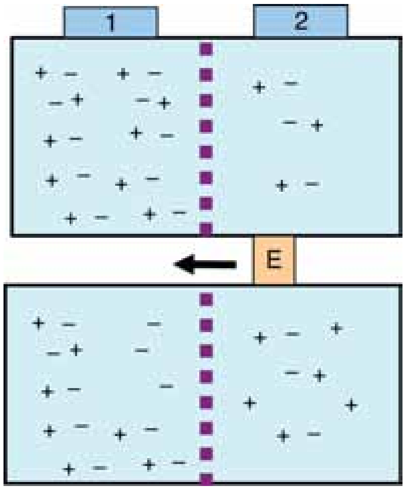

Fig. 2. Diagram of the Nernst equation.

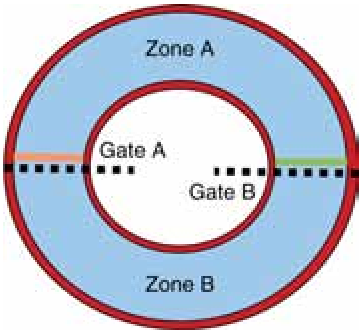

Fig. 3. Diagram for E + MHD minimum energy study.

1. Floodgate A is opened.
2. In the first instance nothing happens because the concentrations of A and B are equal.
3. Now from a hypothetical way each negative ion of zone B can be taken and it is pushed to it through the cationic membrane to put it in zone A.
4. It continues doing this until a certain value of Nernst potential is reached.
5. Now floodgate A is closed.
6. Making a balance of the energy that has been consumed until now it is possible to be said that it is equal to the work of moving ions and therefore equivalent to the Nernst potential that was in the membrane before closing floodgate A.

2.2. Second stage

1. Zone B is put under pressure equivalent to the existing osmotic pressure between zones A and B.
2. Floodgate B is opened. The ions of zone A do not go to zone B because a pressure exists that resists the effect of the osmotic pressure.
3. Now the positive ions of zone B pushes zone A through the anionic membrane.

4. As in the other side a negative ion exists hoping that the positive ions that are being pushed, by electrostatic attraction only the negative ion goes, it does not really have to make force in order to push it, therefore energy in its movement is not consumed.
5. As one takes place the neutralization of all the negative ions is when floodgate B is closed
6. We need to calculate the amount of energy used at this stage. We observe that the energy cost corresponds to the lost energy by the volume of ions that in zone B had pressure and when passing through to zone A they lose pressure.
7. At the end I have two different but well-balanced concentrations electrically.

2.3. Conclusion

- The work needed to take the two zones to a difference of concentration of 100 is equivalent to the Nernst potential that it had in the first stage plus the lost energy, in pressure form, in the volume of ions that crossed the membrane.
- How the energy used in stage 2 is calculated.
  1. If we consider a dissolution of 38 g/l, we will speak of a dissolution that contains 38 kg of salt per m^3 of water.
  2. The density of the sodium chloride is of 2200 kg/m^3.
  3. This means that the volume of 38 L is 17 kg approximately.
  4. Now we need to know the energy lost by those 17 L (1.7% of 1 m^3) that were under pressure and now have disappeared.

In the hypothetical case that we have raised the conversion factor is 0.5 therefore the value of power consumption of stage 2 is 1.150 kWh/m^3 * 0.017 = 0.01955 kWh/m^3.

Following this reasoning the values of energy consumption are given in Table 1.

Table 1
Caption???

Conversion factor	Minimum energy consumption E + MHD (Wt·h/m^3)
0.1	272.53
0.2	288.83
0.3	307.75
0.4	330.44
0.5	358.58
0.6	394.91
0.7	444.54
0.8	519.02
0.9	656.06
0.99	1166.32

This is the theoretical minimum energy required. However, in E + MHD desalination process power is supplied in a special way. The way in which it transmits energy implies that the values set out above must be corrected by the dynamic viscosity of water. The following is the reasoning that explains it.

3. E + MHD working principle

According to magnetohydrodynamics, when a charge goes through a magnetic field (*B*), with a velocity (*V*), the charge suffers a force equal to the vector product of ($B \times V$). The direction of the force depends on the sign (positive or negative) of the charge [9–11].

When the fluid that goes through the magnetic field has positive and negative charges, the positive charges take one direction and the negative ones take the opposite. This movement of charges produces an electric potential between the sides of the fluid. If we link the opposite sides of the fluid we can obtained an electric current.

The industry looks for this current for producing an electrical current. But we are not interested in the electric current. We are interested in the movement of the charges.

We can try to use the second term of the Lorentz force formula [12]. The use of a magnetic field has interesting properties (Fig. 4).

The first one is that we can build a stack of ionic exchange process that does not use an electric current. This is because we can build an ionic exchange stack with no extreme channels.

If there are no extreme channels, then there are no channels with unbalanced ionic charges and we will not need to balance any channel by using an electrical current for the chemical reactions.

So with a simple geometry like this we can get the most important loss in a conventional ion exchange process (the Joule effect) disappear.

The new process that does not use an electric field is

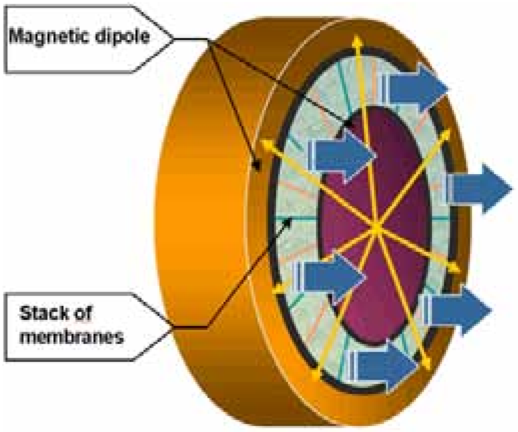

Fig. 4. Diagram of E + MHD configuration.

not a modified electrodialysis. This process is a new ion exchange process.

The configuration of the new stack is the following. There are three main parts. The first is where the interior coils are built. The second part is where the exterior coils are built. These coils produce the radial magnetic field. Between the two coils there is the third part, this element is the cylindrical stack of selective ion exchange membranes.

In this image it is observed as it is the vectorial interaction of magnetic field and velocity of the fluid. This interaction of vectorial fields is produced according to Eq. (3). That one is described graphically in the image shown in Fig. 5.

The trajectory of a particle with charge q under the influence of a magnetic field *B* is directed perpendicularly out of the paper for different values of *q*.

If the load is positive, the Lorentz force is downwards and if the load is negative, the Lorentz force is upwards. Therefore the result is that in each channel (Fig. 6) the equivalent to an electric field due to the displacement of ions takes place.

Figs. 7, 8 and 9 show what happens in the channels of the E + MHD stack. We can see how the ions go from the dilute channel to the concentrate channel.

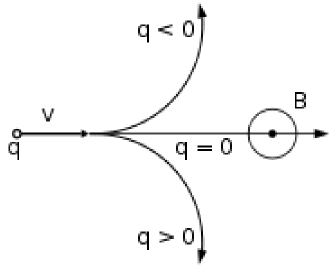

Fig. 5. Diagram of the Lorentz force behaviour.

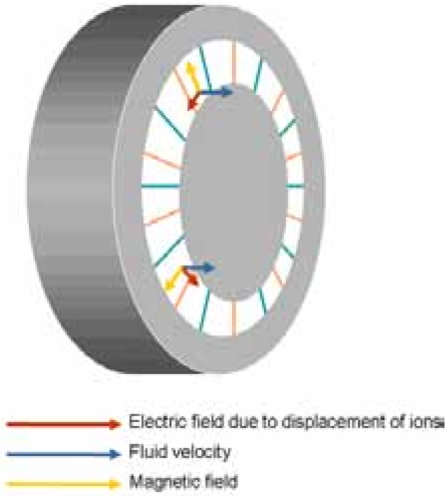

Fig. 6. Diagram of the Lorentz force vectors in each channel.

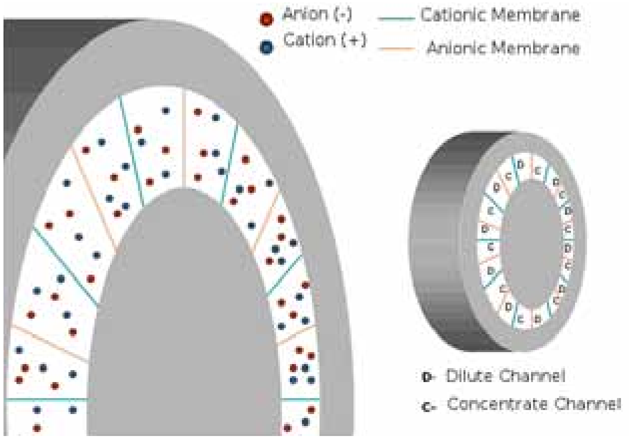

Fig. 7. Presentation of channels in working E + MHD.

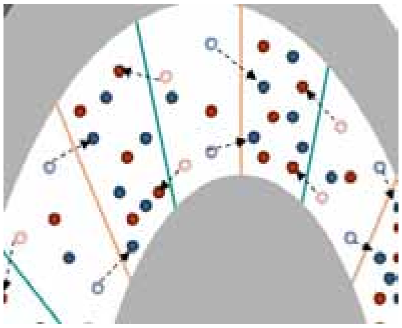

Fig. 8. Channels in the intermediate state when the ions are moving.

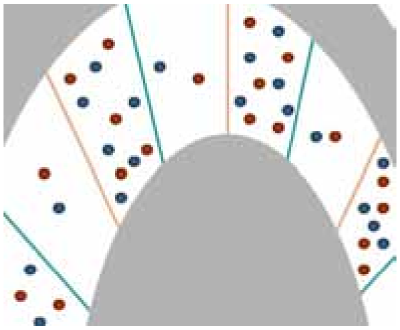

Fig. 9. Channels in the final state when the concentrations are different but electrically neutral.

4. Work and energy consumption mechanisms

With the next figures we are going to explain the mechanism of energy consumption. Firstly for the exposition we can look at a dilute channel.

Consideration for all the cases: The magnetic field goes in a perpendicular direction of the plane of reading of this leaf (Fig. 10).

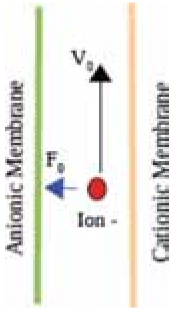

Fig. 10.

4.1. Case 1: Negative ions study

The first effect is the direct result of the Lorentz force. The perpendicular force appears due to the action of the magnetic field and the velocity vector of the ion. As a result of this force on the ion, the trajectory of the ion is modified (Fig. 11).

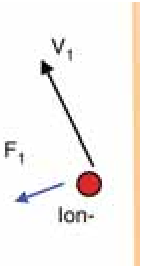

Fig. 11.

At this new moment (T_1) the trajectory is different right away T_0. When the ion takes this new velocity vector, the vector product between the velocity vector of the ion and the magnetic field is different from that at the T_0 moment. It can be represented graphically.

The force that appears at this moment on the anion can be disturbed in its Cartesian components (Fig. 12). The vertical component is a force that is contrary to the velocity vector of the fluid.

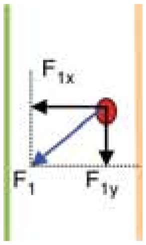

Fig. 12.

This component is of great importance for its physical meaning. It represents the resistance of the ion to modify its trajectory (the first law of Newton). Therefore this component represents the physical mechanism by which the anion absorbs the energy necessary to modify its trajectory.

The horizontal component is the consequence of the change of the trajectory. This horizontal force is the one that must be equal or superior to the Nernst potential so that ion transfer in membranes takes place. The Nernst potential is greater where the difference of concentrations in the channels is greater. Therefore the horizontal force must have a minimum value following the difference of concentrations between channels.

If we increase the velocity or the magnetic field, the component of horizontal force will be greater. It will be able to overcome the Nernst potential majors. In logical form, the vertical component of the force also increases being greater the resistance than it offers the ion to the movement according to the direction of the fluid.

The physical form in which the ion absorbs the energy of the speed of the fluid is in the form of increase of the pressure according to the formula:

$$\nabla P = \vec{j} \times \vec{B} + \eta \nabla^2 \vec{v} \tag{5}$$

where P is pressure, $\vec{j}$ — density charge vector, $\vec{B}$ — magnetic field vector, η —dynamic viscosity, $\vec{v}$ — velocity vector.

According to this equation the loss of pressure is due to two terms: The first term has to do with the Maxwell equations and has direct relation to which the displacement of charges through a conductor produces an induced magnetic field that is against the original magnetic field.

Without entering into numerical values we can give to this term an equal value a $(-j \times B)$. The negative value occurs because we are speaking of charges that have a negative charge. The value of this term cannot be shown graphically for the following reasons.

The second term depends on two factors:

- Dynamic viscosity. This parameter has importance because the loss of pressure in the fluid will be smaller whichever major is the temperature of the water. Of the physical form we could say that from a value of temperature the energy contained in the fluid in the form of temperature helps to the movement of the ion according to the magnetic field.
- Velocity vector.

4.2. Case 2: Positive ions study

In these conditions when the ion goes through the magnetic field the following takes place:

The first effect is due to the Lorentz force. The perpendicular force appears due to the action of the magnetic field and the velocity vector of the ion (Fig. 13).

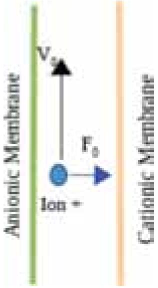

Fig. 13.

As a result of this force on the ion, the trajectory of the ion modifies.

At this point (T_1) the trajectory is different right away T_0. When the ion takes this new velocity vector, the vector product between the velocity vector of the ion and the magnetic field is different from the T_0 moment. It can be represented graphically (Fig. 14).

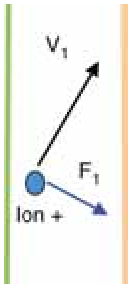

Fig. 14.

The force that appears at this moment on the cation can be disturbed in its Cartesian components. The vertical component is a force that is against the velocity vector of the fluid (Fig. 15).

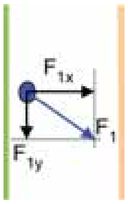

Fig. 15.

This component is of great importance for its physical meaning. This component represents the resistance of the ion to modify its trajectory (the first law of Newton). Therefore this component represents the physical mechanism by which the anion absorbs the energy necessary to modify its trajectory.

The horizontal component is the consequence of the change of the trajectory. This horizontal force is the one that must be equal or superior to the Nernst potential so that the ion transfer in membranes takes place. The Nernst potential is greater whichever major is the difference of concentrations in the channels. Therefore the horizontal force must have a minimum value following the difference of concentration between channels.

If we increase the velocity or the magnetic field, the component of horizontal force is greater. In logical form, the vertical component of the force also increases being greater the resistance than it offers the ion to the movement according to the direction of the fluid.

The physical form in which the ion absorbs the energy of the velocity of the fluid is in the form of increased pressure according to Eq. (5). According to this equation the loss of pressure is due to two terms: The first term has to do with the Maxwell equations and has a direct relation to which the displacement of charges through a conductor produces an induced magnetic field that is against the original magnetic field.

Without entering into numerical values we can give to this term an equal value ($+j \times B$). The positive value occurs because we are speaking of positive charges.

The second term depends on two factors:

- Dynamic viscosity: This parameter has importance because the loss of pressure in the fluid will be lower when the temperature of water is higher. In the physical form we could say that from a value of temperature the energy contained in the fluid in the form of temperature helps the movement of the ion according to the magnetic field.
- Velocity vector.

4.3. Case 3: Case 1 + Case 2

If we take into account the effects explained in case 1 and case 2, we can make the following conclusions:

The first term of Eq. (5) is neutralized when both cases are added. This is due to the fact that the density of positive charges (the cations) and the density of negative charges exists (the anions) that neutralize their effects of induced magnetic field.

With respect to the second term of the equation we can conclude that both terms are added. Since we left from the base of which the number of positive charges and equal to the number of negative charges we have:

$$\nabla P = 2\eta\nabla^2\vec{v} \qquad (6)$$

4.4. Case 4: Sum of the effects between adjacent channels

We have seen what happens in the diluted channel. In the concentrated channel the same happens except for the position of selective membranes. The selective membranes are inverted.

If we pay attention to what happens to both sides of the cationic membrane, we see that the positive ion of the diluted channel tends to go towards the cationic membrane and that the anion of the concentrate channel tends to go towards the cationic membrane. The anion cannot cross the membrane but the cation can cross it (Fig. 16).

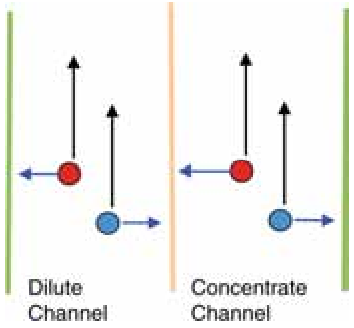

Fig. 16.

This graphical representation is important since it explains how the cation transfer through the membrane takes place. This transfer takes place by electrostatic attraction of the electrical charges on both sides of the membrane.

Now we are going to study what happens to both sides of the anionic membrane (Fig. 17).

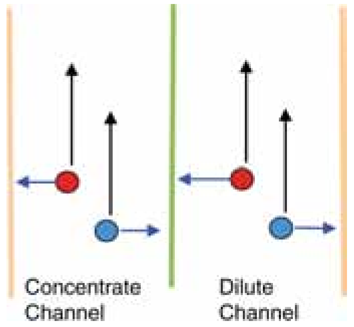

Fig. 17.

We see that the cation of the concentrate channel tends to go towards the anionic membrane and the anion of the diluted channel tends to go towards the anionic membrane. The cation cannot cross the membrane but the anion can cross it.

This graphical representation is important since it explains the anion transfer through the membrane. This transfer takes place by electrostatic attraction between the electrical charges on both sides of the membrane.

4.5. Conclusions

- This system of desalination fulfils the condition of electroneutrality.
- The energy is absorbed directly by the ions that are moved away by a resistance mechanism to the fluid.

This is expressed in a loss of pressure in the fluid.

- The energy absorbed by the ion is necessary to produce the work of displacement (overcoming the Nernst potential).
- Mainly the magnetic field is not affected by the magnetic fields induced by ions and cations because these neutralize each other.
- If we increase the magnetic field or the velocity, we increase proportionally the capacity of the ion to move overcoming the Nernst potential. But it also increases proportionally the energy absorbed by the ion through the fall of pressure in the fluid. The direct consequence of this is that the value of the magnetic field and velocity will have to be the adapted to the Nernst potential that we want to gain since we will be incurring unnecessary losses.
- It also shows that an increase in fluid temperature supports movement of ions (due to the presence of dynamic viscosity in the equation). This implies that part of the energy that has the fluid as heat is transferred to the ion in its movement. This point has a great impact on energy consumption and the ability to use renewable energy in a desalination system with these characteristics.

$$\nabla P \times \mathrm{Vol} = 2\eta \nabla^2 \vec{v} \times \mathrm{Vol}$$

$$\mathrm{Vol} = \mathrm{Area} \times \mathrm{Length}$$

$$P = \frac{F}{\mathrm{Area}}$$

$$\frac{F \times \mathrm{Area} \times \mathrm{Length}}{\mathrm{Area}} = 2\eta \nabla^2 \vec{v} \times \mathrm{Vol} \tag{7}$$

$$F \times \mathrm{Length} = 2\eta \nabla^2 \vec{v} \times \mathrm{Vol}$$

$$\frac{\mathrm{Energy}}{\mathrm{Vol}} = 2\eta \nabla^2 \vec{v}$$

With this fix the minimum energy required values are as shown in Table 1.

5. Energy lost in the E + MHD desalination process. Quantifying losses

In desalination there are energy losses which must be taken into account. Then we introduce the thermodynamic irreversibilities that exist in the E + MHD desalting process.

The energy losses are:

1. Losses by the Donnan potential to the passage of ions through the membranes of ion selectivity.
2. Losses on hydraulic performance of real physical device.

5.1. Energy consumption in ion transport through ion exchange membranes

For the study of energy consumption we will use the theory of Theorell, Meyer and Sievers (TMS theory) [13], for the study of energy losses in the membranes. This theory works in potential and was developed for the study of electrodialysis. The reason we use this theory to study energy consumption in the E + MHD process lies in the following features of this theory:

1. In this theory the membrane ion mobility is assumed constant. In the case of electrodialysis this assumption is far from reality because the ion mobility is linked to the electric charge density. In the case of E + MHD process the mobility is linked to the homogeneity of the magnetic field. So if we assume that the magnetic field is constant so is the ion mobility.
2. Further, the theory does not concern the ohmic potential gradient as driving force operating in electrodialysis. This situation corresponds to zero current density circumstances in which an electric current is interrupted in the electrodialysis system. This assumption is not true in the case of electrodialysis but it is true in the case of the E + MHD.
3. This theory is based on the Donnan equilibrium phenomena.

Reading of this feature shows that E + MHD behaviour can be studied using this theory.

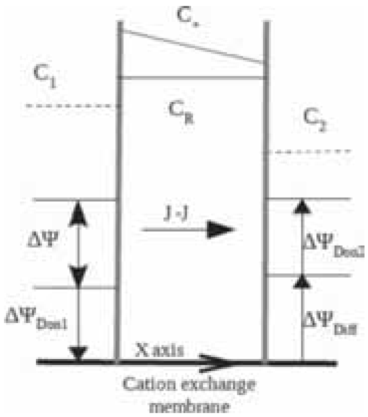

Fig. 18.

A cationic membrane is immersed in a solution of monovalent cations and monovalent anions as reflected in Fig. 18. The ions are transported by diffusion from high concentration of the membrane into the solution through the membrane. The mobility of ions in the membrane is so small that it can be a Donnan equilibrium at the membrane–solution interface. The flow of ions in the membrane is expressed by the Nernst–Planck equation. It is assumed that there is a membrane electroneutrality.

Membrane potential is due to ion transport:

$$\Delta\psi = -\Delta\psi_{\text{Don1}} + \Delta\psi_{\text{Don2}} + \Delta\psi_{\text{Diff}} \equiv$$

$$\frac{-RT}{F}\bar{\mu}\ln\frac{C_2}{C_1}\frac{\sqrt{C_R^2+4C_1^2}+\bar{\mu}\bar{C}_R}{\sqrt{C_R^2+4C_2^2}+\bar{\mu}\bar{C}_R} \tag{8}$$

$$\frac{-RT}{F}\bar{\mu}\ln\frac{\sqrt{C_R^2+4C_1^2}+\bar{\mu}\bar{C}_R}{\sqrt{C_R^2+4C_2^2}+\bar{\mu}\bar{C}_R}$$

where $\Delta\Psi$ = membrane potential due to transport of ions across the membrane; $\Delta\Psi_{\text{Don1}}$ = Donnan potential due to concentration break from the solution towards the membrane; $\Delta\Psi_{\text{Don2}}$ = Donnan potential due to concentration break from the solution towards the membrane; $\Delta\Psi_{\text{Diff}}$= Donnan potential due to concentration break from the membrane towards the solution; R = gas constant; T = temperature; F = Faraday Ct; C_2 = concentration dissolution of arrival; C_1 = concentration of exit solution; C_r = concentration in the membrane.

Schematic representation of a membrane in equilibrium according to the principles is mentioned above.

$$\bar{\mu} = \frac{\bar{\mu}_{\text{cat}} - \bar{\mu}_{\text{ani}}}{\bar{\mu}_{\text{cat}} + \bar{\mu}_{\text{ani}}} \tag{9}$$

where μ = mobility; cat = cationic mobility; ani = anionic mobility.

The study makes the following assumptions:

$$\lim_{\bar{C}_R/C_1\to\infty}\Delta\psi = -\frac{RT}{F}\ln\frac{C_2}{C_1} \tag{10}$$

C_R is the concentration of groups of ions in the membrane. $C_2/C_1 = 0.1$.

This will meet the following limits:

When the concentration jump (inner membrane concentration/solution concentration) tends to infinity, the above equality is true. This occurs when the ion has to pass from the solution into the membrane and is known by the name of Donnan potential. This is the dominant process when an ion has to pass from the solution to the membrane.

In the opposite case the jump tends to zero concentration:

$$\lim_{\bar{C}_R/C_1\to\infty}\Delta\psi = -\frac{RT}{F}\bar{\mu}\ln\frac{C_2}{C_1} \tag{11}$$

C_R is the concentration of groups of ions in the membrane. $C_2/C_1 = 0.1$. There is other equality. This is the typical case where the ion has to pass from inside of the membrane into the solution. This process is also known as the dispersal potential. These limits are represented in Fig. 19.

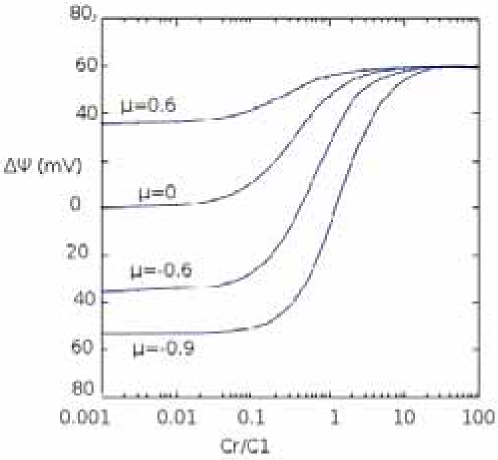

Fig. 19.

Fig. 19 is for the case that the break between the solution concentrations C_1 and C_2 is equal to 0.1. In the case of seawater desalination the break between the solution concentrations C_1 and C_2 is at least 0.01. As the concentration ratio is affected by a natural logarithm adaptation of the graphic results before our case will be made by multiplying the values obtained from the graph by a value equal to 2.

In the E + MHD process negative ions must pass through the cationic membrane and the positive ions must pass through the anion membrane. So to calculate the work lost in the membrane in the E + MHD process, losses in the two membranes should be taken into account.

Let us calculate the membrane potential due to transport of ions in the cationic membrane. In the cationic membrane (negative ions will pass) the mobility of negative ions will be close to 1. However, the mobility of positive ions will be close to 0. With this we will assume that the values sought are on the curve where the ion mobility ratio is equal to –0.9.

In the cationic membrane Donnan potential as the graph is equal to 60 mV. As stated previously, in our case we must multiply this value by 2, therefore the Donnan potential = 120 mV.

The diffusion potential for our case will be 0.55. Multiplying by 2 we have the potential spread = 110.

The Donnan potential of reducing the potential for dissemination obtains a membrane potential due to transportation equal to 10 mV.

In the case of the anionic membrane we should operate similarly. In this case the graph does not show the progression of the curve when the mobility ratio is equal to 0.9. But the evolution of the curves on the graph to predict the potential of diffusion is equal to 55 mV and the Donnan potential is equal to 60 mV.

Following the line of reasoning followed by the calculation of the membrane potential due to transport of ions in the cationic membrane can predict that the value in the anionic membrane shall be 10 mV.

Adding the above potential we have to potential losses due to transport of ions through the membranes, in the case of a jump of concentration equal to 0.01, is equal to 20 mV.

5.2. Energy and exergy lost in the process of ion exchange E + MHD

In the previous section we have obtained the value of the potential lost during the passage of ions through the membranes in the E + MHD process. To translate this potential value lost in a ratio of energy lost during a process of desalination, (m^3 produced water/kWh energy consumed), we can use the calculation process for the loss of exergy in electrodialysis proposed by El-Sayed [14].

Thus using the values of the concentration jump from the previous chapter:

$C_2/C_1 = 0.01$

Energy loss is obtained in step membrane of ions: 499.63 kWh/m^3 at a temperature of 15°C.

5.3. Hydraulic performance losses

Other energy losses are caused by hydraulic losses due to friction of water on the walls of the E + MHD desalination device.

These losses are directly related to the geometry of the device. The hydraulic losses of the prototype will be 254 Wh/m^3 with a conversion factor of 0.5 (fresh water/total water used).

6. Expected total consumption for the E + MHD desalination process

If we add the concepts of:

- Minimum energy necessary for the E + MHD desalination process.
- Lost energy by the passage of ions through selective membranes.
- Loss of hydraulic performance.

we will have a fairly accurate idea of the real minimum energy required in a real E + MHD desalination process (Fig. 20).

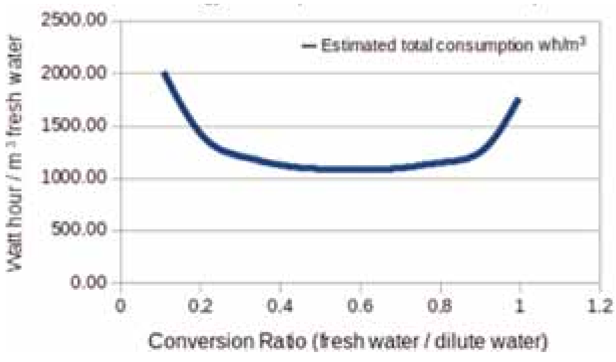

Fig. 20. Real energy consumption in the E + MHD desalination process.

7. Conclusions

Firstly, we have presented a theoretical mechanism for the desalination of seawater and we have theoretically treated topics like:

- Minimum energy consumption.
- Irreversibility of the process presented.
- Electrochemical and mechanical mechanisms involved in the process presented.

The process presented here has interesting features. Theoretically it is an alternative for desalination with a lower energy cost than current systems. The energy saving expected is 50% with respect to reverse osmosis.

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