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Novel design and modeling of a photovoltaic hydro electromagnetic reverse osmosis (PV-HEMRO) desalination system

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ABSTRACT

Reverse osmosis (RO) desalination systems are widely used to provide suitable water for drinking and irrigation especially in countries having an arid climate and receiving low quantities of rain. There are two main difficulties of use of these (RO) desalination systems: the first is the effect of the high salt concentration of feed water which causes membrane scaling and the second is the need for high pressure causing high electrical energy consumption. Therefore, to guarantee optimum operating conditions with the use of advanced control, to ameliorate both the quantity and quality of the product water and to reduce energy consumption, we propose three novel contributions in this paper. The first consists of a design of a photovoltaic hydro electro magnetic reverse osmosis (PV-HEMRO) desalination system. Instead of individual systems (HM and RO) alone as they are described in literature, this new system combines the principle of separating ions by electromagnetic forces and the principle of reverse osmosis by membrane separation. The use of a photovoltaic energy source to feed the system assures a low water product cost. The second consists of the use of an electromagnet instead of a permanent magnet to allow us to vary the magnetic field. The third contribution is the subsequent validation by experimental results of models given in literature. This validation allows us to introduce advanced control and optimization purposes for the desalination process.

Keywords: Hydro electromagnetic; Desalination; Photovoltaic; Modeling; Control

1. Introduction

The desalination industry has been developed the last few years and some applied research has been carried out to ameliorate both the quantity and quality of drinkable water [1,2]. Among these industries, we find the thermal based desalination processes [3], electro dialysis processes, multi-stage flash distillation process [4] although their importance, these methods require higher energy and do not offer a good quality. The best alternative to date is desalination by reverse osmosis as almost half of the world's installed desalination capacity is in reverse osmosis plants. Despite this process requiring high electrical energy consumption when the salt concentration differences between feed water and product water is excessive, the recovery of water entering decreases to 15% [5]. This is the case of the major of RO desalination process. Higher salinity provokes higher osmotic pressure π than requires higher applied pressure P which must be sufficient to overcome the osmotic pressure π. For brackish water, reverse osmosis operating pressure is between 15 and 25 bars with an energy requirement near 3 kwh to product 1 m^3 of water. Sea water operating pressure is between 50 and 60 bars. Although the advantages in quality and quantity of the reverse osmosis desalination, it presents many disadvantages such us the energy requirement, the membrane scaling and the environment pollution caused by the rejected water. The main solution to overcome these problems is to add a hydro electromagnetic (HEM) desalination process able to decrease the feed water salt concentration. Thus, the operating pressure decreases and the quantity of product water increases. Furthermore, it doesn't require high

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energy and the whole system will be compatible with the use of renewable energies. Besides, we avoid membrane fouling as the salt quantity in feed water is reduced.

Several preliminary studies can be found in the literature [6–8] where the use only of magnetic technology for desalination was described. Although this method is suitable for production of irrigation water which doesn't require a profound purification, the hydro magnetic desalination alone can't offer a good quality drinkable water.

Concerning the modeling of each part of the PV-HEMRO desalination system, many models have been established for only RO desalination systems to facilitate the implementation of a control loop [9–12]. The majority of these models are representatives such us inputs-outputs models and they don't explain physical phenomenon and don't allow the control of some parameters.

The present modeling study proposes analytical expressions of each part of the PV-HEMRO desalination system; these expressions will facilitate the establishment of a control model [13]. This paper is organized as follows: First we present a design of the whole system and the technical relation between its components. The second part of this paper deals with the analytical expression of the physical phenomenon principle of both of the two methods: hydro electromagnetic and reverse osmosis desalination. The third section is devoted to simulation and experimental results in order to validate the given models.

2. Design of the photovoltaic hydro electromagnetic reverse osmosis desalination system

The system diagram shown in Fig. 1 is composed by three parts as follows:

- A photovoltaic generator
- Hydro magnetic subsystem
- RO-desalination unit

The photovoltaic generator provides the DC voltage necessary for the two other parts. The PV panel is equipped by an electrical adaptor. This one represents the electronic devices which convert the DC voltage to the AC voltage necessary to feed the motor pump which applies feed pressure P in excess of the osmotic pressure π which results from the difference between the salt concentration of the feed and the product water.

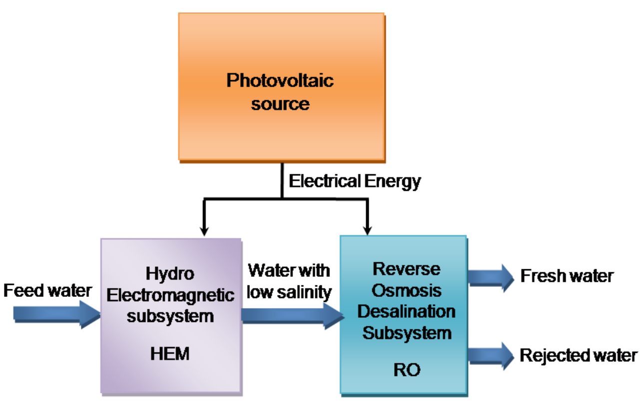

Fig. 1. Diagram of the photovoltaic hydro electromagnetic reverse osmosis (PV-HEMRO) desalination system.

The hydro magnetic module is a remarkable tool to separate ions by magnetic phenomena in all conductive solutions such as salt water. This process installed upstream of reverse osmosis can actually reduce the salt concentration by a factor of 30% for a single passage through. Our target is to reach a factor of 50%; thus, we can start industrial production. The reduction of salt concentration for reverse osmosis feed water protects membranes and decreases the energy consumption. For the hydro electromagnetic subsystem we have proposed the use of an electromagnet fed by the PV generator instead of permanent magnet in order to allow the increase of the magnetic field and so the increase of electromagnetic strength allowing separate of feed water cations and anions.

The reverse osmosis process is most commonly known for its use in drinking water purification. It's based on membrane technology and can theoretically achieve perfect exclusion of salt particles and other effluent. Moreover, reverse osmosis involves a diffusive mechanism, so that separation efficiency is dependent on solute concentration, pressure and water flow rate.

3. PV-HEMRO desalination system modeling

As it is composed by three components, modeling the whole systems consists of presenting the model of each part of the system

3.1. Model of PV generator

To provide the wanted DC or AC voltage to the HEMRO desalination system we have used a photovoltaic generator which is a series-parallel association of photovoltaic cell modules as we have detailed in [9]. The PV generator is coupled to a solar battery through a charge regulator. The use of the battery can avoid the problems of intermittent solar energy. The equivalent circuit of the PV generator is given in Fig. 2.

The analytical expression of the electrical equivalent diagram is

$$I_{pv} = I_{ph} - I_s \left[\exp\left(q \frac{\left(V_p + R_s I_p\right)}{V_t} \right) - 1 \right] - \frac{V_p + R_s I_p}{R_{sh}} \quad (1)$$

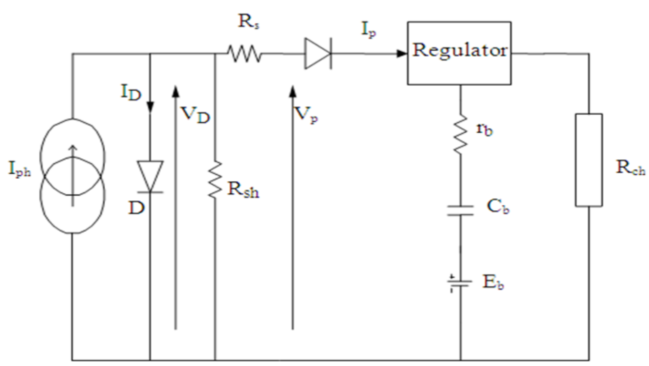

Fig. 2. The electric diagram of the PV panel.

3.2. Model of hydro electromagnetic process

As its name indicates, this new process is based on the combination of hydrodynamic and electromagnetic forces applied on the concentrated feed water flowing in a pipe. When we add the perpendicular action of magnetic field B (teslas) and the instantaneous velocity of the feed water v (m/s), the charged ions in feed water such as (Na^+, Ca^{2+}, K^+, Cl^-, CO_3^{2-}, SO_4^{2-}, …) having an electric charge q (Coulombs) are transported by the action of Abraham-Lorentz force given by the following equation in term of magnetic field and neglecting the electric field.

$$F = qvB \tag{2}$$

As it is not charged, pure water is unaffected by the magnetic force, so it keeps its direction, while the salt concentrated water is pushed by the electromagnetic field then get moves outward. The trajectory of each charged particle depending on its sign is shown in Fig. 3.

As the turbulent flow would remix the ions and can product an internal electric field, the laminar flow is considered good although low speed. Therefore, we must increase the electromagnetic field value B to overcome this limitation. In [7] there is a proposition of a permanent magnetic module which provides a magnetic field of the order of 5 Tesla.

There is also an approach of modeling of the power consumption by the use of Nernst's Law where the potential difference U between the product water (low concentration) and the feed water (high concentration) is given below:

$$\Delta U = E_{fw} - E_{pw} = -\frac{RT}{Zf} Ln \frac{C_f}{C_p} \tag{3}$$

where, E_{fw} and E_{pw} are respectively the potential of both of feed water *(f)* and product water *(p); R*, perfect gas constant; T, absolute temperature (Kelvin); f, Faraday constant; Z, ion charge (Coulomb); C_f and C_p are the concentration of both of the feed and the product water, respectively.

The power of the HEM process can be estimated by the equation:

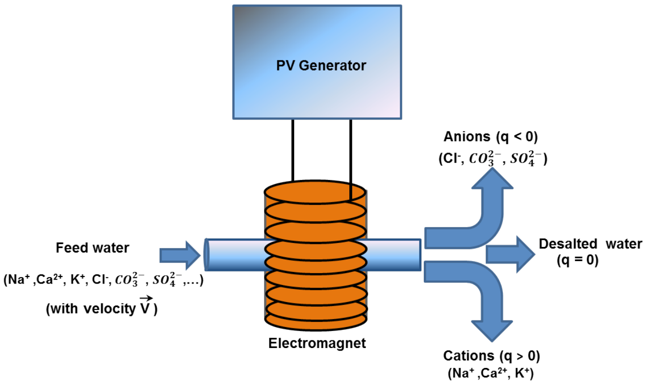

Fig. 3. Water ion trajectory under the effect of electromagnetic force.

$$\int_0^t P\,dt = \int_0^t F\,v\,dt \tag{4}$$

Another approach of modeling a permanent magnet using the Colombian model was given in [14]; this model can be used to calculate the magnetic potential in all points in space.

The electromagnet is an electric magnet which can be controlled by changing current intensity. It is constituted by a solenoid and often of a part of ferromagnetic material called a magnetic circuit. When an electric current passes through the solenoid an electromagnetic field is created and channeled by the magnetic circuit. The advantage of the electromagnet is the possibility of automatic control. By control of the current intensity, we can modify the magnetic field value which is our purpose in this research. The Eq. (5) gives the relation between the electromagnetic field B and the electric current intensity I_{pv} given by the photovoltaic panel (see Eq. (1)).

$$B = \frac{\mu N}{L} I_{pv} \tag{5}$$

where μ is the magnetic permeability(H.m⁻¹); N is the solenoid spiral number; L is the solenoid length (m); I_{pv} is the photovoltaic current (A).

Than manipulating expressions (2) and (5) the electromagnetic force $\boldsymbol{F}$ applied on water ions depends on photocurrent $\boldsymbol{I}_{pv}$ by expression (6) below:

$$F = \frac{\mu N}{L} qvI_{pv} \tag{6}$$

Then, we can control the photovoltaic current I_{pv}, if we want to control the force F.

3.3. The RO desalination unit model

3.3.1. Composition of the RO system

In literature there are several studies which introduce modeling approaches detailed in [9]. However, the developed models are representative and they are not based on the physical laws of the diffusion phenomena. We present in this section of the paper the fundamental laws relative to each part of the RO desalination system to facilitate the introduction of controllable models in future studies. In [15] a decomposition of the RO desalination system into three principal parts is proposed. These parts are the brine side, the membrane side and the permeate side as demonstrated in Fig. 4. where (F: flow rate, T: temperature, P: pressure and C: concentration; p: permeate side, f: feed and m: membrane).

3.3.2. The established RO model

A. Gambier et al. has presented in [15] the overall flowrate, concentration and the feed pressure for the three parts of the RO desalination system then deduced the physical model of the whole system by the expressions below:

$$F_f = F_b + F_m \tag{7}$$

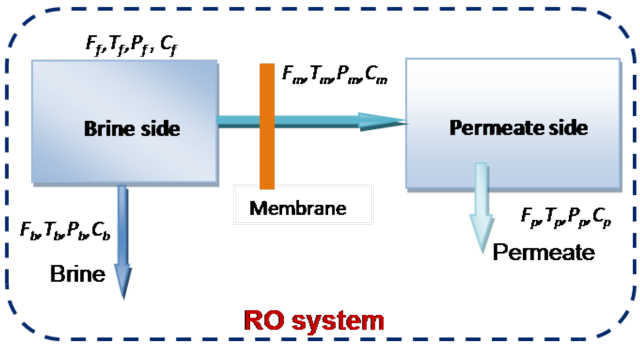

Fig. 4. The RO desalination decomposition diagram.

$$F_m = F_p \tag{8}$$

$$\frac{dC_p}{dt} = \frac{F_m \times (\varepsilon C_b - C_p)}{m_p} \tag{9}$$

$$\frac{dC_b}{dt} = \frac{1}{m_b} \times \left[F_f \times \left(C_f - C_b\right) - F_m \times \left(C_p - C_b\right)\right] \tag{10}$$

$$\frac{dP_f}{dt} = \frac{1}{L_b} \times \left(-\phi \times F_f\right) \tag{11}$$

with

$$L_b = \frac{32 \times \eta_b \times l_b^2}{d_i^2 \times P_{\max}} \tag{12}$$

$$\phi = \frac{128 \times \eta_b \times l_b}{\pi \times \rho_b \times d_i^2} \tag{13}$$

$$F_m = B' \times C_f + A' \times (P_f - \Delta\pi^*) \tag{14}$$

where A' and B' are respectively the transport solvent and solute parameters given below

$$A' = A_0 \times \rho_p \times e^{a_T \times \frac{T_m - T_0}{T_m}} \tag{15}$$

$$B' = B_0 \times e^{b_T \times \frac{T_m - T_0}{T_m}} \tag{16}$$

4. Experimental results and model validation

4.1. Simulation results and discussion

The multi input, multi output HEMRO desalination system model is shown in Fig. 5. The two fundamental input parameters are the feed water F_f flow and the brine pressure P_b; the two fundamental quality parameters are the product water concentration C_p and flow rate F_p.

The model was simulated by Mathlab software. The evolution of these two parameters is presented as follows.

The results consist of a comparison between the salinity and the flow of the product water from brackish water in two cases:

The first case consists of the use of RO desalination without the use of the hydro electromagnetic (HEM) system as shown in Fig. 6. The RO feed water salinity is C_f = 10 kg/ m^3, the water product salinity is C_p = 0.45 kg/m^3, where the product flow is almost F_p = 1800 l.h^{-1}.

The second case consists of the use of the HEM desalination process combined to the RO desalination system. This HEM system first reduces firstly the salt concentration of the feed water by almost 50%, C_f = 5 kg/m^3, then the use of the RO desalination system reduces the product water salinity to almost C_p = 0.2 kg/m^3. The product water flow was not affected and it keeps the same value of almost F_p = 1800 L.h^{-1}. Fig. 7 shows that the use of the HEMRO desalination system makes the product water salinity decrease to almost the half of this salinity when we only use the RO desalination system for the same feed water salinity.

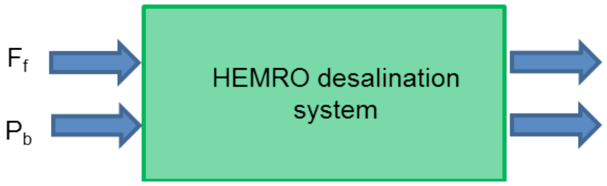

Fig. 5. The input output model of the hydro electromagnetic reverse osmosis desalination system.

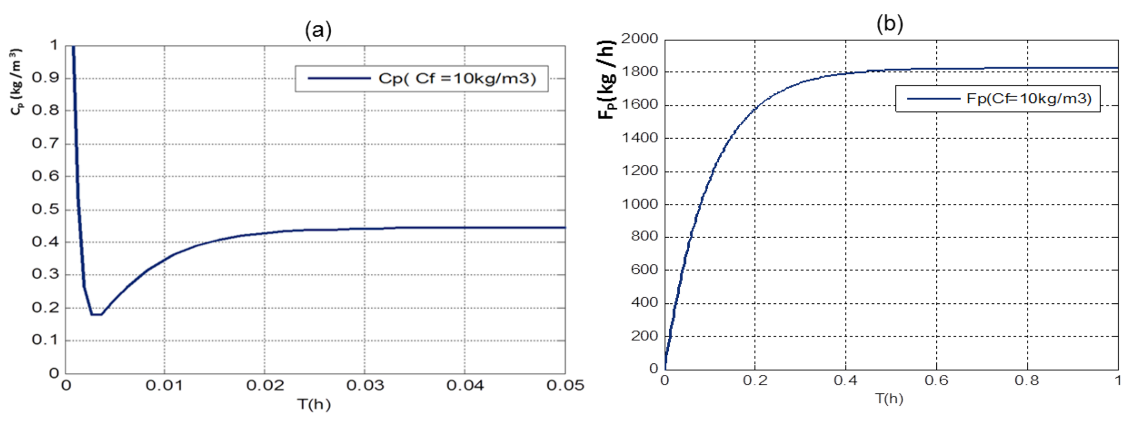

Fig. 6. (a) The product water salinity (C_p) and (b) the product water flow (F_p).

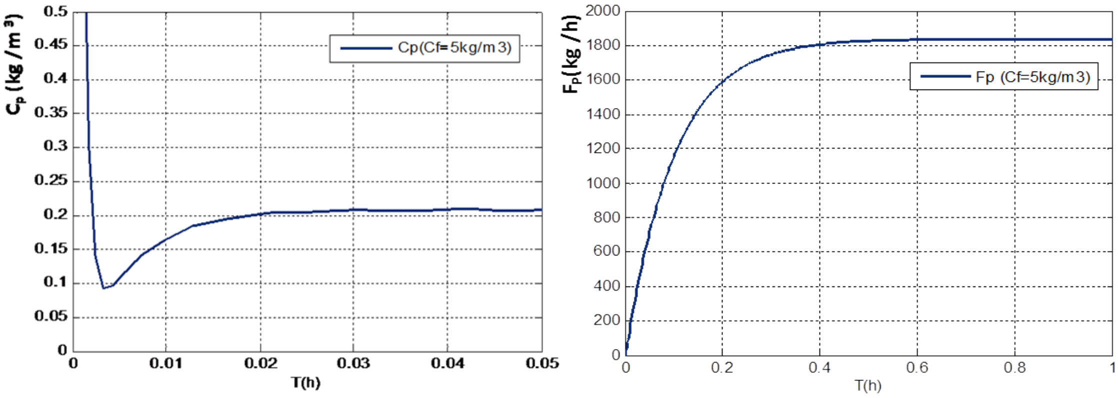

Fig. 7. (a) The product water salinity (C_p) and (b) the product water flow (F_p).

4.2. Experimental results and discussion

The RO desalination experimental plant was installed in research center of energy technologies (Fig. 8).

To validate the salinity behavior we have chosen a feed water salinity equal to 5 kg/m^3, the same as the HEM system output water salinity. It is the maximum salinity value that we can introduce in our small experimental plant. With a data acquisition system, we have measured the product water salinity. Fig. 9 shows its behavior vs. time. This platform is equipped with sensors able to measure the permeate water salinity C_p and the permeate flow rate F_p. Experimental values are stored in measure files then used to represent curves by Math lab software.

Compared to the model simulation result mentioned in Fig. 7(a) we can deduce the following: first, the two final values of the product water salinities given by the model simulation and measured by the experimental plant are the same, (Figs. 7, 9). Second, the hydro electromagnetic desalination system has reduced the feed water salinity from 10 kg/m^3 to almost 5 kg/m^3 to be used by the plant. Thus we have avoided a large loss of water quantity and we have protected the environment from the salted water rejected if only the reverse osmosis process is used.

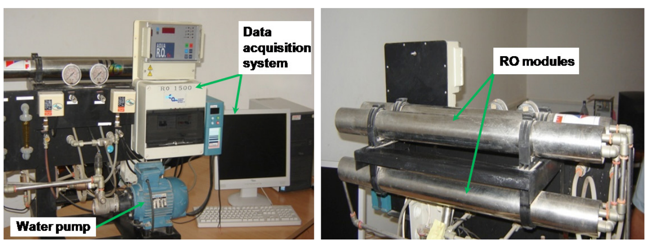

Fig. 8. Photo of the hydro magnetic reverse osmosis desalination system.

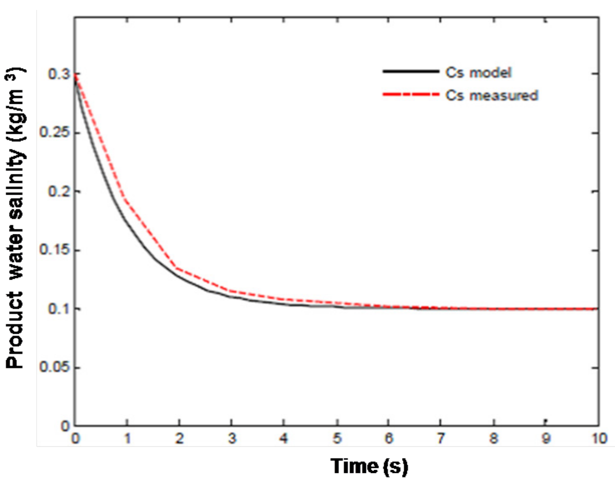

Fig. 9. Evolution of product water salinity.

5. Conclusion

In this work a new coupling between a HEM and RO desalination system is proposed to gather the advantages of the two processes and to overcome their disadvantages. Furthermore, the whole system provides huge quantities of quality potable water with a minimum of energy consumption at a low cost and without affecting the environment.

The prospects of the coupling of renewable energy and HEMRO desalination systems show a flourishing future. The analytic expressions and the elementary models given in literature for each subsystem will simplify the introduction of a dynamic knowledge model that we will develop in future research.

By simulation and experimental result the PV-HEMRO desalination system is in perfect synergy with locations where the water is of a bad quality and most needed. Such a system will be a perfectly adequate solution to provide potable water to the majority of rural areas and remote villages.

The perfection of the system and the integration of advanced control strategies based on the established model will be the second phase of this study and will be necessary to operate the system at optimum conditions and to control both the quantity and the quality of the product water.

Symbols

$C^*_{p,b}$	—	Thermal capacity average (kJ kg^{-1} K^{-1})
d_i	—	Fiber intern diameter (m)
F_{pb}	—	Loss of water between brine and permeate side (kg h^{-1})

F_f — Flow rate of feed water (kg h^{-1})
F_m — Flow rate in membrane side (kg h^{-1})
C_b — Concentration in brine side (kg m^{-3})
I_p — Photo produced current (A)
I_{ph} — Photo-Current (A)
I_s — Reverse saturation current (A)
l_b — Brine tube length (m)
m_b — Water mass in brine side (kg)
P_b — Brine pressure (Pa)
P_f — Feed pressure (Pa)
P_{max} — Maximal pressure (Pa)
Q — Elementary charge (C)
Q_b — Heat (W)
R_s — Serial resistance due to surface state of the PV generator (Ω)
R_{sh} — Shunt resistance due to junction face (Ω)
T_b — Brine temperature (K)
T_f — Feed temperature (K)
T_p — Permeate temperature (K)
V_p — PV generator voltage (V)
V_t — Thermodynamic potential (V)
η_b — Water viscosity (kg m^{-1} h^{-1})
p_b — Rejected water density (kg m^{-3})

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