

**Application of Soret Effect in Optimum  
Desalination Process**

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## **Abstract**

The ocean makes up 70 percent of the earth's surface and accounts for 96 percent of the water on the planet. Unfortunately this water cannot be consumed. It is oversaturated with salt.

Desalination is the process of turning salty ocean water into drinking water. With 783 million people lacking access to clean water and more areas facing severe droughts, desalination can be the answer of this problem. But like other major industrial processes, desalination has environmental impacts that must be understood and mitigated. The effects on the marine environment associated with the construction and long-term operation of seawater desalination plants, including withdrawing water from the ocean and discharging the highly concentrated brine. With that disadvantage a more optimum and environmentally responsible mechanism is needed to supply clean water.

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## Introduction

Throughout the world, water scarcity is being recognised as a present or future threat to human activity and as a consequence, a definite trend to develop alternative water resources such as desalination can be observed. The most commonly used desalination technologies are reverse osmosis (RO) and thermal processes such as multi-stage flash (MSF), multi-effect distillation (MED), and Solar Pond Desalination [4]. Although those mechanism has been used in many places there are still some limitations that need to be overcome.

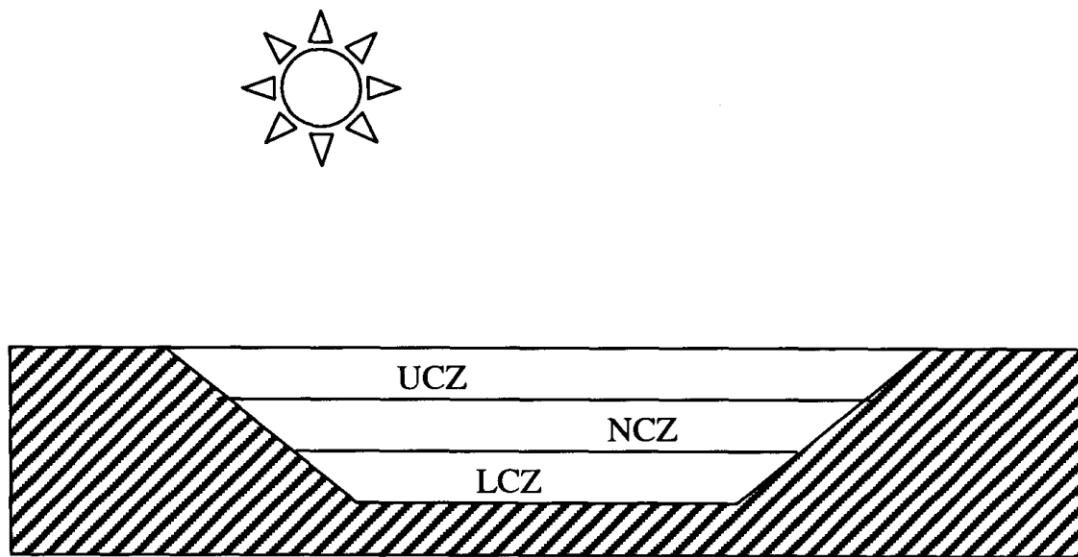


Figure 1: Diagram of a salt-gradient solar pond showing the various layers.

## Disadvantages of Solar Pond:

The accumulated salt crystals have to be removed periodically and this adds maintenance expense [6]. Solar ponds require a significant amount of land area to function properly (Muñoz and Almanza, 1992). It can only operate in sunny days and if the site is shaded by tall trees or

building, it may not work properly [12]. Proper algae and dust removal is needed as the thermal efficiency of a solar pond sturdily depends on the clarity of the pond [8]. For instance, leakage of the brine could foul a local freshwater supply. They are also not very efficient, and should be constructed close to the equator so that the solar radiation will be fairly constant throughout the year.

The salt-gradient solar pond can be used to generate electricity from the thermal difference between the hot and cold layers of the pond by using a power cycle. A cycle is defined in thermodynamics as a series of processes that have no net change of state. In other words, although a system may undergo changes of state, if these changes return it to its original state, the system may be said to have undergone a cycle. A power cycle is a particular cycle that extracts work from a circulating fluid and transfers it to the surroundings. (As opposed to a refrigeration or heat pump cycle, which transfers energy to a circulating fluid from the surroundings.) However, to understand the limits of a power cycle, a basic understanding of the first and second laws of thermodynamics is necessary.

The first law of thermodynamics states that although the energy in the system may change forms (e. g. from heat to work), the total amount of energy is conserved. The second law states that heat energy is not spontaneously transferred from a cooler body to a warmer body. Since a cycle can have no net energy change, the net amount of work must equal the net heat transfer of the cycle.

The heat transfer is controlled by the absolute temperature difference between the hot and cold layers of the pond, which in turn controls the amount of work (and thus power) that can be

extracted from the cycle. The thermal efficiency of a power cycle is defined as the ratio of work to heat input, which is kept from unity by the heat that is rejected from the cycle. The second law of thermodynamics leads to a concise theoretical maximum for the thermal efficiency of a power cycle, known as the Carnot efficiency:

$$\mu_{max} = 1 - \frac{T_{cold}}{T_{hot}}$$

The pond's power cycle has the good criteria of desalination process and the potential to generate a modest amount of power at a reasonable cost; however, the tolerances involved in the design require careful attention to details to insure that a reasonably cost effective design is implemented [7].

### **Soret Effect**

A temperature gradient applied to a liquid mixture not only causes heat flux but also gives rise to a diffusion current of the constituent particles or molecules, which drift along temperature gradients, some condensing in the hotter and some in the colder. The resulting separation of the molecules causes the gradient parallel or anti-parallel with respect to the temperature gradient. Generally, a particle moves from hot to cold, but the reverse is also seen under some conditions. For example: concentration rate or the heating gradient. This microscopic phenomenon, known as Soret effect. The mass flux of the solute in a binary mixture is given as:

$$J_T = -\rho(D\nabla c + D_T c(1 - c)\nabla T) \quad (1)$$

where  $\rho$  is the mixture density,  $D$  is the molecular diffusion coefficient,  $c$  is the mass fraction of the solute,  $D_T$  is the thermal diffusion coefficient, and  $T$  is the absolute temperature. At equilibrium,  $J_T = 0$ , and equation (1) reduces to:

$$\nabla c = -\frac{D_T}{D} c(1 - c)\nabla T. \quad (2)$$

The factor  $D_T/D$  is called the Soret coefficient ( $S_T$ ) [10].

Because of the combined actions of two diffusing quantities an impressive onset of convection has been observed. Rayleigh-Bénard instability in solution with Soret effect appears as an oscillatory mode. This phenomenon has been extensively studied both experimentally and theoretically. It has been observed that the Soret varies its sign. Some peculiar behavior has been observed due to the change of the Soret sign. For salty water of concentration less than 5wt%, it has been shown that the Soret effect is zero at 12 °C; being negative below this temperature and positive above 12°C. In some sense, the solute in the upper half of the salty layer migrates down, unlike of what happens in the lower half. Such arguments may raise many questions on the possibility to use this phenomenon in problems of practical and technological interest, such as desalination. [1].

### Thermal Analysis

We consider a horizontal layer of uniform salinity, which is initially at a temperature of  $T = 12^\circ\text{C}$  and a mass fraction  $N \leq 5\text{wt}\%$ . This layer is confined between conductive two plates which are separated by a distance  $d$

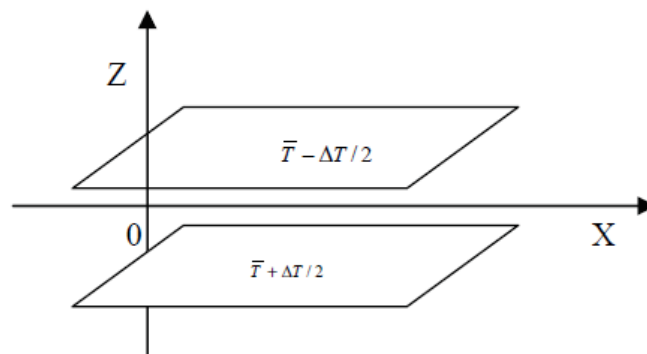


Figure 2 : Sketch of salty layer conditions

Relaxation times can be identified and modeled with the aim of understanding the behavior of the solution inside the pores as a function of concentration. In desalination it can be described as time for which a distribution of salt occurs and remains stationary [9].

$$\tau \approx \frac{d^2}{\xi \cdot (1 - N_m) \cdot D_m \cdot \Delta T^2} + \frac{d^2}{16\pi^2 \cdot \alpha} \quad (3)$$

In the motionless basic state, a linear temperature distribution is established throughout the salty layer. It is defined by:

$$T(z) = \epsilon \Delta T \cdot z^* + \bar{T} \quad (4)$$

When a macromolecular solution or a colloidal suspension is placed in a uniform-temperature gradient the dispersed particles migrate, focusing at either the cold or hot side [2]. When the equilibrium state is reached (for a time  $t=t$  that is given in section 2.2), the salt distribution equation is defined by:

$$\frac{\partial N}{\partial z^*} + S_T \cdot N i (1 - N i) \frac{\partial T}{\partial z^*} = 0 \quad (5)$$

The Soret coefficient increases linearly with the temperature as expected for a hydration entropy [3]. It can be described as :

$$S_T = \xi (T - 12) \quad (6)$$

The salt profile at the steady state is described by:

$$N(z) = N_{\max} - \xi_T \cdot N i \cdot (1 - N i) \epsilon^2 \frac{\Delta T^2}{2} z^{*2} \quad (7)$$

For a concentration of  $N = 28.5 \cdot 10^{-3}$  the Soret coefficient is given by:

$$S_T = 10^{-5} * [-119 + 11.05 * T - 0.064 * T^2 + 10^{-4} * p * (3.20 - 8.48 * T + 0.0532 * T^2)] \quad (8)$$

When the effect of the pressure and the temperature of second power are negligible, the Soret coefficient can be reduced to the following form:

$$S_T \approx 11.05 * 10^{-5} (T - 10.77) \quad (9)$$

The maximum concentration of salt is evidently located in the zone where the Soret effect vanishes. Definitely, it is the zone of the temperature equal to 12oC that is located in the centre of the solution. The concentration at the edges of the salty layer and after a time t, is

$$N(z = \pm \frac{d}{2}) = N_{\max} - \xi_T . Ni . (1 - Ni) \frac{\Delta T^2}{8} = N_{\min} \quad (10)$$

To determine the value of Nmax and Nmin, we use the fact that the average salt concentration in the salty layer is independent of time that is equal to Ni. Hence, it is given by the following equation:

$$3Ni. = 2N_{\max} + N_{\min} \quad (11)$$

$$N_{\max} = Ni + \xi_T . Ni . (1 - Ni) \frac{\Delta T^2}{24} \quad (12)$$

$$N_{\min} = Ni - \xi_T . Ni . (1 - Ni) \frac{\Delta T^2}{12} \quad (13)$$

For the maximum separation (i.e. after a time t or at steady state), the concentration at the center of the salty layer and the edges of salty layer are

$$N(z = 0) = N_{\max}, \quad N(z = \pm \frac{1}{2}) = N_{\min} \quad (14)$$

The difference of concentration between the extreme values is

$$\Delta N = N_{\max} - N_{\min} = \xi_T . N_i . (1 - N_i) \frac{\Delta T^2}{8} \quad (15)$$

The dispersion of solute depends on the temperature gradient across the liquid layer is shown by the equation above [1].. . For enhancing its efficiency, DT must be maximized.

The concentration distribution can be described by equation:

$$N(z) = N_i [1 + \xi . (1 - N_i) \frac{\Delta T^2}{8} (\frac{1}{3} - 4z^{*2})] \quad (16)$$

### **Desalination Process**

The process of desalination, which we are dealing with, is a new form of separating fresh water from salty water by using Soret effect. The main purpose of the evaluation of the concentrate dispersion from the point of discharge is to establish the size of the zone of initial dilution (ZID) required to dissipate the discharge salinity plume to near-ambient seawater TDS levels and to Concentrate Management determine the TDS concentrations at the surface, mid-level of the water column, and at the ocean bottom in the ZID [13].

The dispersion of the components of the solution under heating allows us to separate mechanically the more salty and the less salty. Also the potential dispersion of marine discharges must be carefully assessed in order to minimise risks to local ecosystems and water quality. The dispersion of effluent typically occurs over a wide range of spatial and temporal scales. Close to the outfall, mixing processes are governed by the initial characteristics of the effluent and the

outlet (the near-field), and both the spatial and temporal scales associated with mixing are relatively short [11].

The solution of the salty water at 12°C is pumped in the rectangular cell. Then, a temperature gradient is applied on the layer. The gradient can be induced by thermoelectric devices for example. The top and the bottom faces of the experimental cell are heated and cooled down; however, the lateral walls are insulated. The average temperature of the gradient is maintained at 12°C. Besides, we considered the case of temperature gradient for which convection can't appear. These conditions induce the separation of solute by Soret effect in opposite direction. Beyond the zone of temperature of 12°C the solute migrates to this zone, and accumulates in the center forming a bulb of brine water. When we extract, from the layer of salty water, the bulb of brine water and repeat the process on the remaining water, this can yield potable water.

### **Desalination System Unit**

Sea water desalination through solar radiation distillation process can achieve low cost and sustainable fresh water for remote dry areas. In conventional passive solar stills, the solar radiation passes through the transparent cover and supplies heat to sea water with limited back reflection. The evaporative heat transfer between the water surface and the glass cover produces the distillate by means of film type condensation at the inner surface of the glass cover [5]. The advantages of Soret effect desalination system is the low energy consumption. Moreover, the energy needed by desalination process can be supplied with the electrical energy produced by solar energy plants, and this in the aim to reduce the energy charge as much as all devices can work with low voltage energy [1]. .

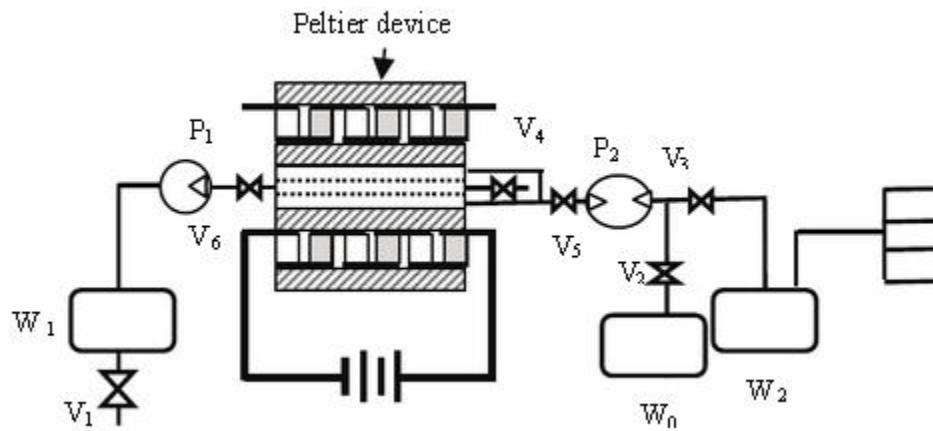


Figure 3 : Design of Unit of Desalination System

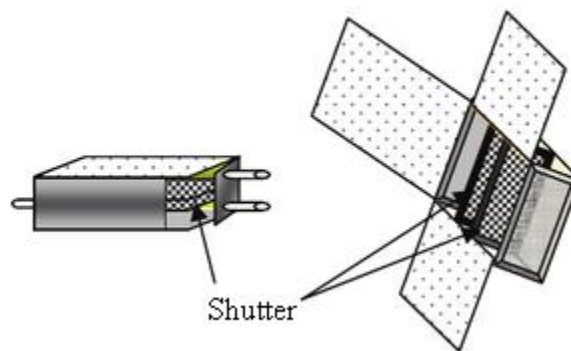


Figure 4 : Cut-away of the Cell

The heat and cold supplied at the boundaries of the solution layers can be produced temperature gradient for which convection cannot appear. These conditions induce the separation of solute by Soret effect in opposite direction. Other side of the desalination plant can be provided by electrical energy produced by solar energy. Having set such plant, the distillation process is normally performed according the following steps:

The salty water is pumped into the cell, until it will be filled, and then it is preserved of all external connections (i.e. the valve V5 and V6 are closed). Subsequently, the thermal gradient

is applied on the salty layer. A distribution of salt appears in the medium and evolves until it reaches a steady state. Ultimately, the shutters are closed and the brine can be drawn out from the central zone of the cell. However, the water in the peripheral zones is collected and recycled for a second distillation.

By using thermoelectric system (i.e. Peltier device). Such device needs a small current that can be supplied from solar energy by using a Solar Panel. In spite of the low COP of the device that is of order of 0.1, it can produce enough of cold and heat that can maintain an average temperature of 12C throughout the solution. The desalination process is intended so to perform a series of separation stages. Each solution obtained should be processed again a certain number of times. Each stage accomplishes the same function; what we call here a unit of desalination. , we give a sketch of the unit of desalination system. The main component in the desalination unit is the cell into which the separation is performed. The particular dimension of the cell is its thickness. . In the case where convection can occur, the thickness should satisfy the condition of non-onset of convection ( $Ra < Ra_{cr}$ ).

### **Unit Arrangement**

The arrangement of the unit of the desalination is as follows. A small pump (P1) is connected to the central zone of the cell which serves to discharge the more salty water from the cells and delivers it to what we call a brine collector tank (W1). The pump (P2) is connected to the cell, which pumps the less salty solution from the cell into the tank (W2), besides it fills the cell up of the brut salty solution carried from the tank (W0). The valve (V1) serves to drain the more salty water, however, the valves (V2and V3) serve to control the liquid flow from the cell to the tank

(W2) and from the tank(W0) to the cell, respectively. The valve V4 is used for evacuating air from the cell and the valves (V5 and V6) are used to isolate or link the cell with the others component of the system. Two shutters are installed symmetrically inside the cell.

The cell is divided in three zones: central zone and two peripheral zones. The shutters can isolate the central zone from the two peripheral zones, when the salt is accumulated in the middle. The shutters have been inserted to perform the best solution as a trap of brine accumulated by Soret effect. Notice that all electrical energy needed for the components of the desalination plant can be provided by electrical energy produced by solar energy[1].. .

Having set such plant, the distillation process is normally performed according the following steps: The salty water is pumped into the cell, until it will be filled, and then it is preserved of all external connections (i.e. the valve V5 and V6 are closed). Subsequently, the thermal gradient is applied on the salty layer. A distribution of salt appears in the medium and evolves until it reaches a steady state. Ultimately, the shutters are closed and the brine can be drawn out from the central zone of the cell. However, the water in the peripheral zones is collected and recycled for a second distillation process. This operation is repeated in the plant, till the quality of the water will be what we call potable [1]..

## Conclusion

In the coming decades, surging population growth, urban development, and industrialization will increase worldwide demand for fresh water, requiring new sources of water. Although several options currently exist to augment freshwater sources—including the treatment of low-quality local water sources, water recycling and reuse, water conservation, regional water transfers that do not adversely impact the environment, and the implementation of smart land-use planning—these options alone will not be enough to meet this need. Seawater desalination offers the potential for an abundant and steady source of fresh water purified from the vast oceans. With the analysis of the thermodynamics and desalination method has been presented, desalination by using Soret effect is technically feasible. Further improvements in technology, energy use, and concentrate treatment will allow a wider application of Soret effect desalination to inland and rural communities.

## Nomenclature

|                |                                               |
|----------------|-----------------------------------------------|
| $S_T$          | Soret coefficient                             |
| $k$            | Boltzmann constant                            |
| $G$            | Gibbs free energy                             |
| $S$            | Entropy                                       |
| $V$            | Volume                                        |
| $J_T$          | Mass flux in thermal diffusion equation       |
| $\rho$         | Mixture density in thermal diffusion equation |
| $D$            | Molecular diffusion coefficient               |
| $c$            | Mass fraction of solute (NaCl)                |
| $D_T$          | Thermal diffusion coefficient                 |
| $T$            | Absolute temperature                          |
| $P$            | Pressure                                      |
| $\mu_i$        | Chemical potential of component $i$           |
| $n_i$          | Moles of component $i$                        |
| $G_{ionic}$    | Gibbs free energy of ionic shielding          |
| $Q_{eff}$      | Effective charge                              |
| $\lambda_{DH}$ | Debye length                                  |
| $A$            | Particle surface area                         |

|                 |                            |
|-----------------|----------------------------|
| $\varepsilon$   | Relative permittivity      |
| $\varepsilon_0$ | Permittivity of free space |
| $e$             | Electronic charge          |
| $N_A$           | Avogadro's number          |
| $t$             | Temperature in °C          |

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