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On the Feasibility of Ocean Brine Pool Power Stations

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The demonstrated existence of vast brine pools in a number of places in the ocean basin around the world offers an interesting opportunity to the production of power from ocean which has not been yet considered. The attractiveness of these vast deposits of brine lie in the fact that can be readily dissolved with the surrounding top waters extracting the spontaneous osmotic mixing energy released. In addition, osmotic engines can pumped out the brackish streams by buoyancy without the add of pressure exchangers (PEXs) as is required in current pressure retarded osmosis (PRO) technology and then simplifying significantly the overall process. Utilizing a simplified physical model, a first estimation for the density of power per unit of membrane area was calculated.

Keywords. *Salt Basins; Osmotic energy; Ocean power*

I. INTRODUCTION

The oceans represent a vast and largely untapped source of energy [1],[4], in the form of surface waves, [5]-[7]; thermal [8], osmotic power [9], and today new approaches for ocean power are investigated in the light of new technological developments, [10]. Among new sources for ocean power which has not yet been considered neither explored so far, is the latent potential hidden within the oceanic brines pools. The demonstrated existence of these vast brine pools in a number of places in the ocean basin around the world offers an interesting opportunity to the production of power from ocean so far unexplored.

Oceanic brines pools are large areas of brine on the ocean basin in which salinity can be as high as eight times greater than the surrounding ocean and they are formed essentially by salt tectonics when thick layers of salt -up to 8 km thick in some places, come into contact with seawater, they dissolve, and form brines up to 8 times saltier than seawater. These heavy brines flow out of the seafloor in channels that result in puddles, pools, and even lakes of brine. Oceanic basins, are found around the world, [11] (see Fig. 1), these include: the South Atlantic basins of West Africa and Brazil, the north Caspian area, and with particular importance in Europe (the North Sea, Mediterranean basin), USA (with the great Gulf of Mexico basin), and the Middle East (the Gulf of Suez, Red Sea, the Persian Gulf, the Zagros Mountains of Iran and Iraq among others). The salinity of those basins could be up to eight times greater than the surrounding ocean as is the case for the Red Sea basin, [12].

The attractiveness of these vast deposits of brine lie

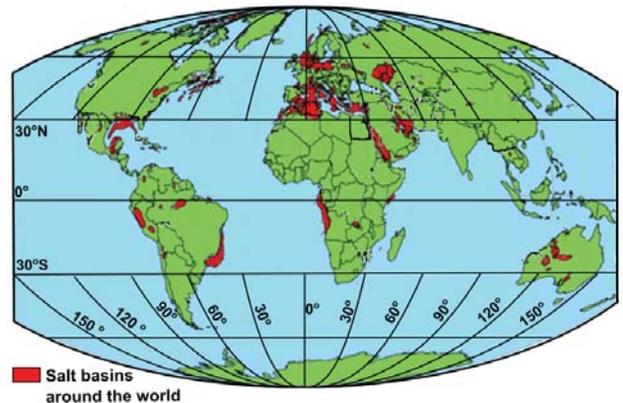


FIG. 1: Salt basins around the world. From [11]

in the fact that could be readily dissolved with top (less salty) waters and then extracting the spontaneous mixing energy released by using an osmotic power engine. In addition, the ocean basin -as infinite pool reservoir, allows a new simplified osmotic engine in which the brackish streams is pumped out by the resulting buoyancy and then without the add of pressure exchangers (PEXs) as is required in current technology.

The object of this work was a first upper limit on the osmotic power which can be attained in those ocean basins. For the sake of illustration, in Fig. 2 the basis of the idea is pictorially sketched. In this figure, a simple osmotic engine is placed into the basin and top-waters out of the basin -and then with minor salinity, are pumped towards the bottom by the osmotic pressure, then the brackish stream (or by product of the mixing of the brine with the top waters) which is less salty than the surrounding

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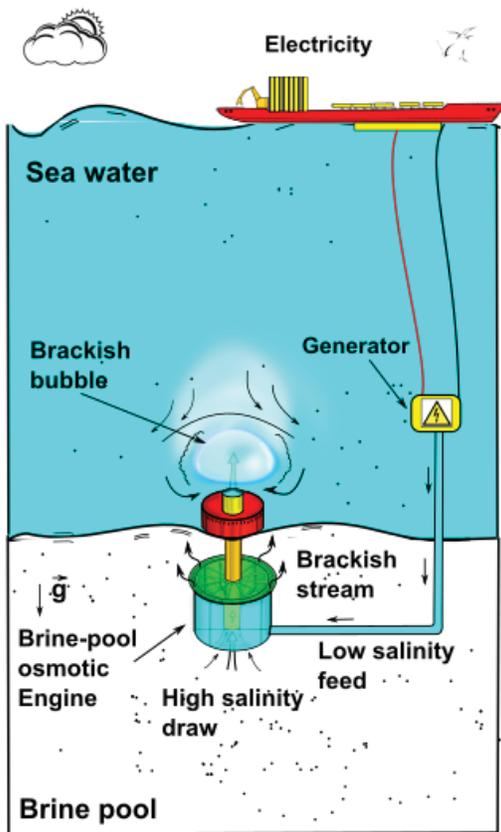


FIG. 2: Sketch of a brine pool power station

brine, and then lighter, is propelled by buoyancy far away from the engine. By using a simple turbine, an electrical power output can be obtained.

II. MATERIALS AND METHODS

A. Maximum extractable energy from ocean brine pools

To begin with, in a thermodynamically reversible process, the maximum extractable energy from the mixing could be estimated using the molar Gibbs free energy of mixing ΔG_{nm} which is defined as the energy per mole of mixed solutions generated from mixing two solutions of different salinities in an isobaric and isothermal process,[19]

$$-\frac{\Delta G_{nm}}{\nu RT} = \sum_i x_{i,M} \ln(\gamma_{i,M} x_{i,M}) - \frac{n_F}{n_M} \sum_i x_{i,F} \ln(\gamma_{i,F} x_{i,F}) - \frac{n_D}{n_M} \sum_i x_{i,D} \ln(\gamma_{i,D} x_{i,D}) \quad (1)$$

where ν is the van 't Hoff factor for strong electrolytes (e.g., $\nu = 2$ for NaCl) R is the ideal gas constant; T is the absolute temperature; n_M , n_F , and n_D are the total amounts (in moles) of mobile species in the mixed,

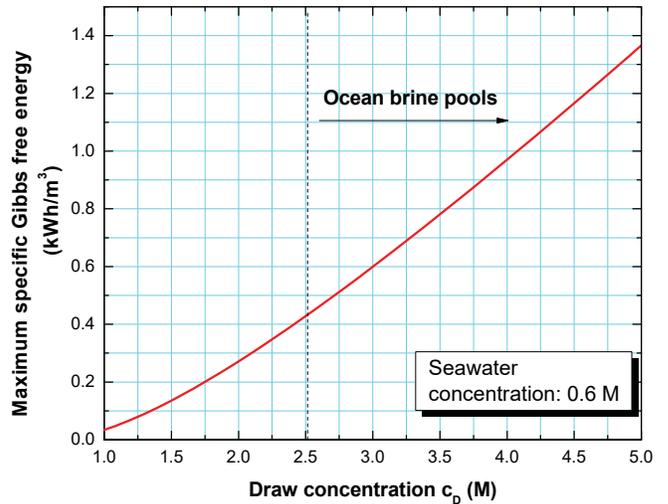


FIG. 3: Specific Gibbs free energy of mixing for the mixing of seawater $c_F = 0.6M$ as a function of the concentration of draw.

feed, and draw solutions, respectively; $x_{i,M}$, $x_{i,F}$, and $x_{i,D}$ are the mole fractions of species "i", in the mixed, feed, and draw solutions, respectively; and $\gamma_{i,M}$, $\gamma_{i,F}$, and $\gamma_{i,D}$ are the activity coefficients of species "i" in the corresponding solutions. If it is allowable to assume a negligible contribution of solute to the volume of the solution, then, the ratio of the total moles in the feed and draw solutions to the total moles in the mixed solution can be approximated by the corresponding volume fractions

$$\phi \approx \frac{n_F}{n_D}$$

$$1 - \phi \approx \frac{n_D}{n_M} \quad (2)$$

and then, the specific Gibbs free energy of mixing per volume of total mixed solution can be rewritten as function of the molar concentrations of the feed, draw, and mixed solutions (c_F , c_D , c_M) and the feed volume fraction ϕ , [17]

$$-\frac{\Delta G_{Vm}}{\nu RT} = c_M \ln(\gamma_{i,M} c_M) - \phi c_F \ln(\gamma_{i,F} c_F) - (1 - \phi) c_D \ln(\gamma_{i,D} c_D) \quad (3)$$

Furthermore, for ideal dilute solutions, the activity coefficients can be approximate as unity, and then Eq.(3) yields

$$-\frac{\Delta G_{Vm}}{\nu RT} = c_M \ln(c_M) - \phi c_F \ln(c_F) - (1 - \phi)c_D \ln(c_D) \quad (4)$$

The maximum ΔG_{vm} can be calculate by differentiating Eq.(4) with respect to ϕ and solving for the value which maximizes ΔG_{vm} , i.e., $\left. \frac{\Delta G_{vm}}{d\phi} \right|_{\phi=\phi^*} = 0$ and yields,[19]

$$\phi^* = \frac{\exp\left(\frac{c_F \ln(c_F) - c_D \ln(c_D)}{c_F - c_D} - 1\right) - c_D}{c_F - c_D} \quad (5)$$

Inserting Eq.(5) into Eq.(4) one obtains

$$-\frac{\Delta G_{V,max}}{\nu RT} = \frac{c_d c_F}{c_D - c_F} (\ln c_D - \ln(c_F)) - \exp\left(\frac{c_D \ln(c_D) - c_F \ln(c_F)}{c_D - c_F} - 1\right) \quad (6)$$

• Discussion

Fig. 3 shows the specific Gibbs free energy of mixing per unit of volume of solution for seawater $c_F = 0.6$ M and $T = 294$ K as a function of the concentration of draw, where for hypersaline ocean brine pools salinities can be found between four to eight times greater than the seawater, i.e., $c_D = 2.4$ M to $c_D = 4.8$ M, respectively. It is seen that the typical osmotic extractable energy from ocean brine pools may be in the range of ~ 1 kWh/m³. If one considers that hypersaline oceanic pools can be as large as 10 m across and up to 20 km long with thickness up to 60 meters as detected in the Gulf of Mexico or the Red Sea, we obtain a storable energy in the pool around ~ 12 GWh, i.e., a power station with a power output of 100 kW could operate day and night for up to 14 years.

III. POWER DENSITY

An important parameter is the density of power per membrane area. As first estimation it can be calculated as follows:

The maximum power density per area of membrane, W_s can be calculated by multiplying the maximum extractable energy per unit of volume given by Eq.(6) by the water flux across the membrane, J_w ,

$$W_s \approx J_w \Delta G_{V,max} \quad (7)$$

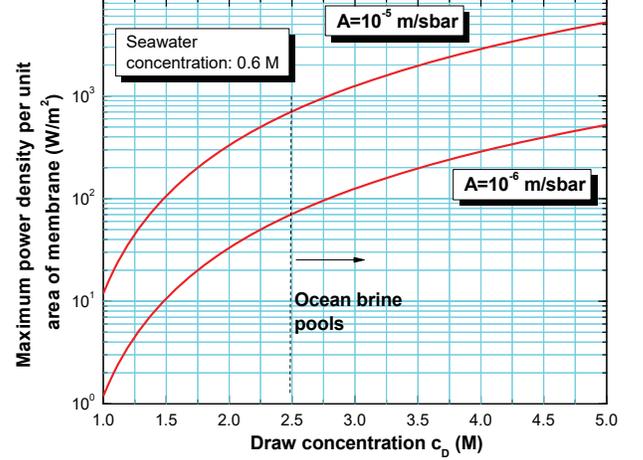


FIG. 4: Power density per unit of area of membrane as a function of the concentration of draw.

The water flux across the membrane per unit of membrane area, J_w (m³/(sm²)) can be defined in terms of the membrane water permeability coefficient A ; the osmotic pressure at the draw side on the membrane active layer, π_D ; the osmotic pressure at the feed side of the membrane active layer, π_F ; and the hydrostatic pressure difference between the column of hypersaline brine and the feed,

$$J_w = A [(\pi_D - \pi_F) - g(\rho_D - \rho_F)\Delta h] \quad (8)$$

where ρ_D and ρ_F are the densities of the brine pool (the draw) and the seawater (the feed), respectively., and Δh is the difference in level between the osmotic engine and the interface seawater-brine pool. The difference of osmotic pressure between the sides of the membrane is related with concentrations as

$$\pi_D - \pi_F = \nu RT(c_D - c_F) \quad (9)$$

Further, for the difference of concentration between the brine and the seawater, the osmotic pressure can be much more higher than the difference in hydrostatic pressure and then the last can be neglected. Thus, the water flux across the membrane, simplifies as

$$J_w = A(c_D - c_F)\nu RT \quad (10)$$

One of the important parameters in Eq.(10) is the membrane water permeability coefficient, and today and active research is developed in optimization of cell length, membrane resistance or the use of nanotubes in membranes in order to increase the water permeability through the membrane for reverse osmosis (RO) process, but nowadays, current commercial technology, membrane

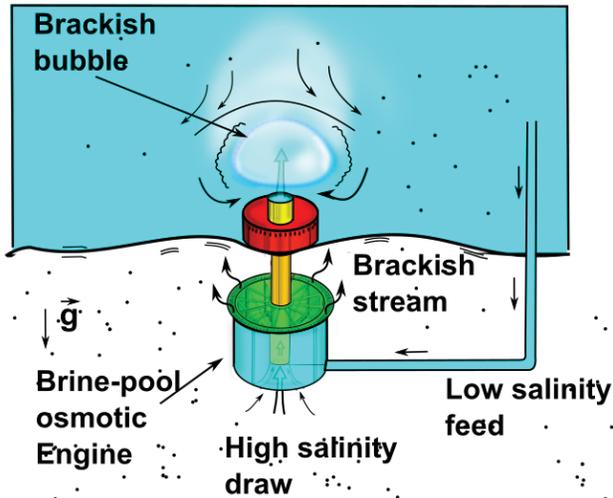


FIG. 5: Sketch of an osmotic pool engine.

water permeability coefficients used in dilute or ideal solutions (e.g., seawater-river water system) can be found between $10^{-6} \text{ m}^3/(\text{m}^2 \text{ s bar})$ to $10^{-5} \text{ m}^3/(\text{m}^2 \text{ s bar})$ which translate into power densities as a function of the concentration of the draw as shown in Fig. 4. Nevertheless the real value for membrane water permeability working with concentrations near saturation (brine pools could be up to 5 M) can departure significantly from commercial membranes used for, say, traditional reverse osmosis (RO process), moreover another operative constraints lead to 20-30% decrease in the specific attainable energy, [18]. In view of all these uncertainties a conservative figure could be around a 50 % of efficiency and then the attainable power density would be between 50 W/m^2 to 500 W/m^2 . This power density are not only significantly higher than those from solar energy with $\sim 20 \text{ W/m}^2$ (as the the Cestas Solar Park in France photovoltaic power station) or wind energy $\sim 4 \text{ W/m}^2$, [20], but besides, energy can be extracted in steady state day and night without interruptions and then avoiding the intermittence problem besetting those renewable energies.

IV. THE OSMOTIC POOL ENGINE

Besides the attractiveness in terms of power density, there is another point in favor oceanic brine pool power stations. As is well known traditional osmotic engines designed for extraction of mixing energy -a process generally referred as pressure retarded osmosis or PRO process, require the use of pressure exchangers (PEXs) in order to increase the operating pressure in the system and pumping the draw, the feed or both solutions through the system, [19]. However, it is easy to see (Fig. 2) that for the specific case of an oceanic brine pool osmotic engine the use of PEX is not longer necessary.

Indeed, the buoyancy force acting on the resulting mixed solution or brackish (due to its lower density in comparison with the surrounding brine) will propel the brackish stream as a *brackish bubble* as pictorially shown in Fig. 5. The motion of this convective bubble will continuously remove the brackish stream. The key point to run continuously this kind of osmotic pool engine is that the mass flow induced by the bubble be equal than the osmotic mass flow across the membrane calculated previously, which may be calculated as follows:

Considers a parcel of mixed solution (from the mixing of the draw and the feed) with concentration c_M an volume V having temperature T and a density ρ_M . It displaces an equal volume of the surrounding brine pool having a concentration c_D and a pool density ρ_D and a temperature T , i.e., we are considering a global isothermal system. The downward force on the parcel is equal to $\rho_M g V$. The downward force on the brine displaced is equal to $\rho_D g V$. The upward force is the same for parcel and displaced brine, $-V \frac{\partial p}{\partial z}$. Hence the net buoyant force (upward) is $V g (\rho_D - \rho_M)$, therefore, the buoyant acceleration is

$$a_B = g \left(\frac{\rho_D - \rho_M}{\rho_M} \right) \quad (11)$$

For the global osmotic analysis, it is convenient to work with changes of concentration rather than changes in density, and it can be made if one considers that the density of NaCl solution bears a linear relation to the concentration, and then a relationship between density and concentration can be defined as $\rho = \rho_o (1 + \epsilon c)$, with $\rho_o = 1000 \text{ kg/m}^3$ and $\epsilon = 3.7 \times 10^{-2} \text{ l/mol}$, therefore $\epsilon c \ll 1$ and thus, Eq.(11) may be rewritten as

$$a_B \approx g \epsilon (c_D - c_M) \quad (12)$$

Taking into account the simplifying assumptions from Eq.(2), we have

$$c_M \approx c_D (1 - \phi) + c_F \phi \quad (13)$$

and the maximum energy extractable is obtained when the feed fraction is equal to the critical fraction $\phi = \phi^*$ given by Eq.(5), which inserting into Eq.(13) yields

$$c_M \approx \exp \left(\frac{c_F \ln(c_F) - c_D \ln(c_D)}{c_F - c_D} - 1 \right) \quad (14)$$

Now, stratified lake and oceanic brines owe their existence to the very slow transport mechanism for salt migration, which is mostly by molecular diffusion, [21]. The time to remove a 95% of initial salinity difference is calculated between 5000 years to 34000 years depending of the concentration and the thickness of saline layer, [21].

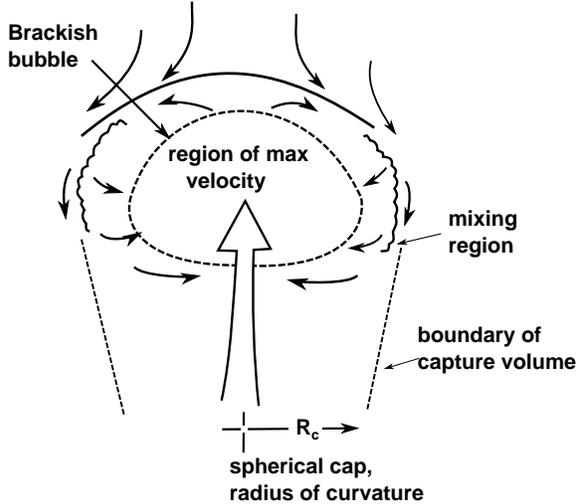


FIG. 6: Structure of a convective bubble, from [22]

Therefore, one can expect that the elementary parcel of mixed solution arising from the buoyant force be shape-preserving, i.e., to have a form which maintains geometrical similarity during much of their development. From this point of view, and as first approximation, the bubble theory, [22], appears appropriate. Fig. 6 is an idealized structure of a convective bubble.

Within the theory of bubble convection, it is argued that the vertical velocity of the bubble depends on its size as

$$v_b = f [a_B R_c]^{1/2} \quad (15)$$

where v_b is the bubble upward velocity of the cap, R_c is the radius of the cap, and f is a dimensionless constant determined experimentally and is close to $f \sim 1$, [22]. Inserting Eq.(11), Eq.(15) becomes

$$v_b = f [g \epsilon R_c (c_D - c_M)]^{1/2} \quad (16)$$

Finally, the induced buoyant flux by the bubble will be approximately $\pi R_c^2 v_b$ and this flux should be equal than the total osmotic flux across the membrane, i.e., $S_m J_w = \pi R_c^2 v_b$, where S_m is the surface of the membrane.

$$R_c \approx \left[\frac{c_D - c_F}{g \epsilon} \right]^{1/5} \left[\frac{R T A S_m}{f \pi} \right]^{2/5} \quad (17)$$

Fig. 7 shows the radius of the bubble cap as a function of the draw concentration and using a membrane water permeability coefficient $A = 60 \text{ l}/(\text{m}^2 \text{ h bar})$.

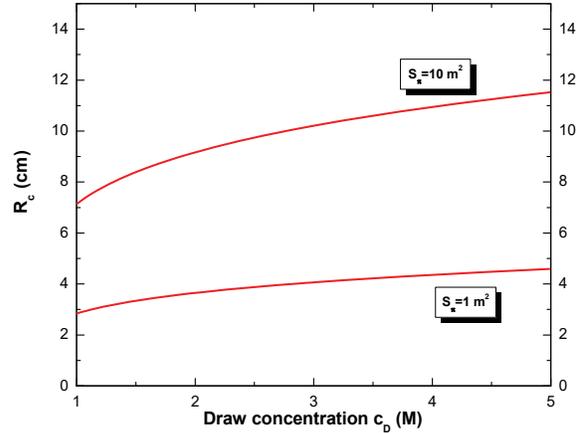


FIG. 7: Radius of the bubble cap as a function of the draw concentration.

V. SUMMARY OF RESULTS AND CONCLUSIONS

In this scoping note, the possibility to harness the latent osmotic potential hidden within the oceanic brines pools which has not yet been considered neither explored is investigated. The attractiveness of these vast deposits of brine lie in the fact that can be readily dissolved with the surrounding top waters extracting the spontaneous osmotic mixing energy released. Some interesting conclusions derived by this preliminary work as follows:

- Power densities in the order of kW/m^2 per unit of membrane area could be attainable.
- A much more simplified osmotic "pool" engine adapted for the ocean basin is possible in which brackish streams is remove form the engine by buoyancy and then eliminating the need of PEX as in traditional approaches.
- Additional R&D is required in order to explore reliable practical and commercial designs.

NOMENCLATURE

A = membrane water permeability coefficient
 ΔG_{nm} = molar free energy of mixing
 ΔG_{nm} = volume free energy of mixing
 R = ideal gas constant
 T = absolute temperature
 x = mole fraction
 n = moles
 c = concentration
 J = water flux across the membrane
 v = velocity

f = dimensionless constant
 g = gravity
 Δh = difference of level
 R_c = radius of the bubble cap and reactor
 ϕ = feed volume fraction
 Π = osmotic pressure
 g = gravity

Greek symbols

ρ = density
 ν = van 't Hoff factor
 γ = activity coefficient
 π = osmotic pressure
 ρ = density

subscripts

D = draw
 F = feed
 M = mixture
 w = water

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