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Ocean Thermal Energy Conversion by Deliberate Seawater Salinization

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Consideration is given to the possibility of ocean thermal energy conversion (OTEC) by the deliberate salinization of surface seawater. The proposed technique is similar to traditional OTEC, with one important exception: rather than cold water being brought from the bottom to the surface, the warm surface water is circulated to the bottom, cooled there, and lifted back to the surface. The entire process is driven by the induced salinity gradient at the surface. As a result, there is no need for a pumping system to bring the cold bottom water to the surface. Two methods are explored for surface salinity enhancement, namely solar evaporation and the direct addition of salt to the seawater.

Keywords. *OTEC, Salinity gradient, Thermal gradient, Osmotic pressure*

I. INTRODUCTION

Since the 1980s, it has been found that the generation of electricity by ocean thermal energy conversion (OTEC) is an unattractive option compared with the cost associated with fossil fuels [1],[2]; as a result, the funding of research into OTEC has been seriously reduced [3], and no large-scale OTEC plants are currently operating in the USA [4]. A comprehensive review of the state-of-the-art in OTEC technology can be found in [5] and [6], whereas for those readers interested in the fundamental aspects of OTEC technology, the classical book by Avery [7] is recommended. Nevertheless, in recent years, OTEC has experienced a significant reawakening. Current OTEC projects include Lockheed Martin's development of a more economically efficient OTEC power system [8]; the project commenced in 2016 by the Korea Research Institute of Ships and Ocean Engineering (KRISO) with a 1 MW OTEC installation off the coast of South Tarawa, part of the Republic of Kiribati in the South Pacific Ocean; or the KRISO's 1 MW OTEC plant as the first practical step toward building a 100 MW commercial system. Finally, worthy of mention, is the project developed by the French BARDOT Engineering Group who has recently signed a contract for the first commercial OTEC system to be installed in an eco-resort in the Maldives, expected to be completed during 2018 [9].

OTEC technology basically consists of pumping cold ocean water to the surface and using the temperature difference between this and the warm surface water to run a thermal engine and generate electricity. Unfortunately, because of the low temperature difference in OTEC ($\approx 20^\circ\text{C}$ or less), the water flow must be very

large to harness useful amounts of heat. For instance, a 100 MW power plant would be expected to pump on the order of 45 metric tonnes per minute [10]. Pumping this volume of water implies a substantial parasitic drain on energy production in OTEC systems where it is estimated that pumping costs about 40% of the total net electricity generated [10]-[12].

The object of this work is to analyze a novel alternative technique for thermal energy conversion by the deliberate salinization of surface seawater. The proposed approach is intended to eliminate the pumping systems used in current OTEC approaches to bring the bottom seawater to the surface. This is possible because, with the proposed technique, no cold water is brought from the bottom to the surface. Instead, the warm surface water is circulated to the bottom, cooled there, and brought back to the surface and being the entire process driven by the induced salinity gradient resulting from the deliberate salinization of the surface seawater.

Two possible methods of enhancing the salinity of the surface seawater will be explored: **(1)** enhancing solar evaporation using a dedicated surface area, as illustrated in Fig. 1, and **(2)** pouring salt brought from, say, a near-shore body of saline brine into the seawater, as shown in Fig. 2.

II. SYSTEM DESCRIPTION

As a starting point, let us consider the scheme depicted in Fig. 1, where salinity enhancement of the surface seawater is attained by enhancing solar evaporation. Initially, warm surface seawater of density ρ_o , salinity s_o , and temperature T_h is partially evaporated. The depletion in water content result in salinity to increase from s_o to, say, s_2 and the density to increase to ρ_2 . We can assume that the water after evaporation remains at the same temperature by considering the heat exchange

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FIG. 1: Sketch of the proposed OTEC concept where the salinization of seawater is generated by enhancing solar evaporation.

with the surrounding ocean, which can be assumed to act as an infinite reservoir.

Now, the salinized water, after falling to the deep ocean (point 2 in Fig. 1) and after passing through a mass and heat exchanger where is cooled at temperature T_c and recovers its initial salinity s_o by mixing with the surrounding deep seawater, then arrives at point (1), with temperature T_c and salinity s_o . The assumption of recovering initial salinity in the mixing is justified because, first, the osmotic pressure favors the low concentration of the surrounding seawater passing through a semipermeable membrane to mix with the saltier water coming from the surface, and second, the ocean can be seen as an infinite reservoir.

Under this simple principle, we can proceed to analyze the feasibility of gaining extractable energy using induced salinity for OTEC.

Let us take the reference density of the warm surface water to be ρ_o . Then, after the salinity of this water is increased by evaporation or pouring salt directly into the seawater (as schematically depicted in Figs. 1 and 2,

respectively), the new density is given by

$$\rho_2 = \rho_o + \nabla_s \rho \Delta s \quad (1)$$

where

$$\Delta s = s_2 - s_o \quad (2)$$

is the percentage gain in salinity and $\nabla_s \rho$ is the variation of density with salinity. Because the salinized water is heavier, it is gravitationally transported to the bottom, where it is cooled and desalinated (by mixing with the surrounding seawater) in a dedicated heat and mass exchanger. The mixing is favored by the forward osmotic (FO) pressure, which pushes the surrounding bottom water (with low or nominal salinity) through a semipermeable membrane.

After mixing in the mass exchanger, and considering that the volume of water recovered its initial nominal salinity, thus the density of the water volume becomes

$$\rho_1 = \rho_o + \nabla_T \rho \Delta T \quad (3)$$

FIG. 2: Sketch of the proposed OTEC concept where a salinity gradient is obtained by dumping salt brought from onshore saline brine directly into the seawater.

where

$$\Delta T = T_c - T_h \quad (4)$$

is the difference between the surface temperature T_h and the bottom temperature T_c , and $\nabla_T \rho$ is the variation of density with temperature.

To move a quantity of water around the system against friction, the hydrostatic difference between the hot and cold water column should at least compensate for the friction losses. Thus, we have

$$(\rho_2 - \rho_1)gH > \Delta P_f \quad (5)$$

where g is gravity, H is the height of the column, and ΔP_f is the pressure drop due to friction losses.

However, as well as controlling the mixing and desalination of the volume of water coming from the surface at the mass exchanger, forward osmosis FO can also be harnessed as an additional pushing pressure source term. This kind of energy is generally referred to as pressure retarded osmosis (PRO) [13]–[18]. In the PRO process, the osmotic pressure difference across the semipermeable

membrane (which increases the flow rate and dilutes the salinized water) can be converted into an increase in pressure by means of bifurcating the increased flow rate using a proper pressure exchanger (PEX) [14].

Therefore, taking into account this additional osmotic pressure, Eq. (5) becomes

$$(\rho_2 - \rho_1)gH + \epsilon \Pi > \Delta P_f \quad (6)$$

where Π is the available osmotic pressure and ϵ is a defined efficiency factor of performing mechanical work by the osmotic pressure.

Using the Darcy–Weisbach equation [19], the friction pressure drop can be calculated as

$$\Delta P_f = \frac{8fL\dot{m}_w^2}{\pi^2 \rho D^5} \quad (7)$$

where L is the total pipe length, f is the pipe friction coefficient, $\dot{m}_w$ is the seawater mass flow, D is the diameter of the pipe, and ρ is a proper average density of the fluid. Thus, Eq. (6) becomes

$$(\rho_2 - \rho_1)gH + \epsilon\Pi > \frac{8fL\dot{m}_w^2}{\pi^2\rho D^5} \quad (8)$$

If we can neglect the horizontal length of pipes, taking into account that the vertical height is much greater, then $L \approx 2H$, and on the other hand taking into account that the water mass flow can be expressed approximately as a function of the power plant as

$$P \approx \dot{m}_w c_p \Delta T_p \quad (9)$$

where P is the power of the plant, c_p is the heat capacity, and $\Delta T_p \approx -\Delta T = T_h - T_c$. Thus, Eq. (8) becomes

$$(\rho_2 - \rho_1) > \frac{16fP^2}{\pi^2\rho D^5 g c_p^2 \Delta T_p^2} - \frac{\epsilon\Pi}{gH} \quad (10)$$

The osmotic pressure at the semipermeable membrane is proportional to the difference in concentration between the seawater and the salinized seawater

$$\Pi \simeq (c_2 - c_o)RT \quad (11)$$

where c_2 and c_o are the ionic molar concentrations (mol per unit volume) of the salinized seawater and the normal seawater, R is the gas constant, and T is the temperature, i.e., $T = T_c$. A reference osmotic pressure may be defined as Π_o , where $\Pi_o = c_o RT_c$ is the approximate osmotic pressure between normal seawater and pure fresh water. The ratio of molar concentrations $\frac{c_2}{c_o}$ may be expressed as a function of their salinities as $\frac{c_2}{c_o} = \frac{s_2}{s_o}$, in which case Eq. (11) becomes

$$\Pi \simeq \Pi_o \frac{\Delta s}{s_o} \quad (12)$$

Finally, the difference $(\rho_2 - \rho_1)$ in Eq. (8) may be evaluated from Eq. (3) and Eq. (1), giving

$$(\rho_2 - \rho_1) = \nabla_s \rho \Delta s - \nabla_T \rho \Delta T \quad (13)$$

This can be inserted into Eq. (10) to give, considering Eq. (12) and after the rearrangement of certain terms,

$$\frac{\Delta s}{s_o} = \left[\frac{16fP^2}{\pi^2\rho D^5 g s_o c_p^2 \Delta T_p^2 \nabla_s \rho} + \frac{\Delta T}{s_o} \frac{\nabla_T \rho}{\nabla_s \rho} \right] \cdot \frac{1}{\Psi_{s_o}} \quad (14)$$

where, for the sake of compactness, an osmotic factor Ψ_{s_o} was defined as

$$\Psi_{s_o} = 1 + \frac{\epsilon\Pi_o}{\nabla_s \rho g H s_o} \quad (15)$$

To obtain some idea of the salinization required as a function of the power plant predicted by Eq. (14), we assume some typical OTEC parameter values: diameter $D = 1$ m; average salinity of seawater $\rho = 1000$ kg/(m³); $s_o = 3.5\%$; $g = 9.8$ m/(s²); $c_p = 4.2 \times 10^3$ J/(kg)(K); $\Delta T_p \approx 20$ K; $\Delta T \approx -20$ K; $\nabla_s \rho = 0.7$ kg/(m³)(%); $\nabla_T \rho = -0.13$ kg/(m³)(K) at a cold temperature of $T_c = 278$ K; typical pipe friction coefficient $f = 0.012$; $\Pi_o \approx 26 \times 10^5$ Pa for the reference seawater with $s_o = 3.5\%$; $H = 1000$ m. The resulting curves are shown in Fig. 3a for the salinization as function of the efficiency of the PRO process for a 100 MW OTEC plant, and Fig. 3b for salinization as function of power plant and with $\epsilon = 0.05$.

It is interesting to see that, for OTEC plants with power up to $P \leq 100$ MW, which is the objective of future OTEC plants, the convective term (second term inside the brackets) in Eq. (14) is the dominant term. We can thus simplify Eq. (14) as

$$\frac{\Delta s}{s_o} = \left[\frac{\Delta T}{s_o} \frac{\nabla_T \rho}{\nabla_s \rho} \right] \cdot \frac{1}{\Psi_{s_o}} \quad (16)$$

If FO is not considered, or when the efficiency is very low, the full system is driven by the convective term. In this case, we have

$$\frac{\Delta s}{s_o} \approx \left[\frac{\Delta T}{s_o} \frac{\nabla_T \rho}{\nabla_s \rho} \right] \quad (17)$$

III. ANALYSIS

Now that the degree of salinization was found as function of the plant power, in this section, we analyze two methods of obtaining this salinity enhancement in the seawater. The first involves enhancing solar evaporation of the surface seawater, and the second considers the direct addition of salt to the water.

A. Salinization by solar evaporation

If the salinization enhancement is attained by enhancing solar evaporation, as illustrated in Fig. 1, then the required evaporation rate may be calculated as follows.

First, from the mass balance at the evaporator (see Fig. 4), we have

$$\frac{\dot{m}_s \Delta t}{\dot{m}_w \Delta t - \dot{m}_{we} \Delta t} = \frac{\dot{m}_s \Delta t}{\dot{m}_{w2} \Delta t} \quad (18)$$

where $\dot{m}_s$ is the mass flow of salt (dissolved in the water); $\dot{m}_w$ is the mass flow of water (the input); $\dot{m}_{we}$ is the mass flow rate of evaporation; $\dot{m}_{w2}$ is the mass flow of unevaporated water (the output); and Δt is the time

FIG. 3: a). Required salinization for a 100 MW OTEC plant as a function of the efficiency of the PRO process. b) Required salinization as a function of the power plant with $\epsilon = 0.05$

FIG. 4: Evaporator mass balance.

interval. However, we know that $\frac{\dot{m}_s \Delta t}{\dot{m}_w \Delta t} = s_o$, i.e., the nominal salinity of seawater, and $\frac{\dot{m}_s \Delta t}{\dot{m}_{w2} \Delta t} = s_2$ is the final salinity. Therefore, Eq. (18) may be rewritten as

$$\dot{m}_{we} = \dot{m}_w \left[\frac{1}{1 + \frac{s_o}{\Delta s}} \right] \quad (19)$$

or, by inserting Eq. (9),

$$\dot{m}_{we} = \frac{P}{c_p \Delta T_p} \left[\frac{1}{1 + \frac{s_o}{\Delta s}} \right] \quad (20)$$

Finally, the feasibility of the evaporative method must be evaluated in terms of the actual capability of producing the required evaporation rate, which ultimately turns out to be dependent on the dedicated surface area.

Many semi-empirical formulations for the evaporation

of water are available; the simplest expression given by Shuttleworth [20] seems preferable:

$$\dot{m}_{we} = 1.15 \times 10^{-5} \left[\frac{m R_n + \gamma \delta_e (1 + 0.536 u_w)}{\lambda_v (m + \gamma)} \right] \times A_s \quad (kg/s) \quad (21)$$

where m is the slope of the saturation vapor pressure curve (kPa/K); R_n is the net irradiance (MJ/(m²)(day)); u_w is the wind speed (m/s); δ_e is the vapor pressure deficit (kPa); λ_v is the latent heat of vaporization (MJ/kg); A_s is the total surface area (m²); and γ is the psychrometric constant (kPa/K) given by

$$\gamma = \frac{0.0016286 \cdot p}{\lambda_v} \quad (kPa/K) \quad (22)$$

The vapor pressure deficit is given by

$$\delta e = (e_s - e_a), \quad \text{or};$$

$$\delta e = (1 - e_r) e_s \quad (23)$$

where e_s and e_a are the saturated vapor pressure of air and the vapor pressure of free flowing air, respectively. The former is given by [21]

$$e_s = 0.13 \exp \left(21.07 - \frac{5336}{T_a} \right) \quad (kPa/K) \quad (24)$$

and therefore

$$m = \frac{de_s}{dT_a} = \frac{693.68}{T_a^2} \exp \left(21.07 - \frac{5336}{T_a} \right) \quad (kPa/K) \quad (25)$$

FIG. 5: Salinator mass balance.

Finally, by inserting Eq. (20) into Eq. (21), we obtain the required surface area A_s as a function of the power plant

$$A_s \approx \frac{4.34 \times 10^4 \cdot \lambda_v(m + \gamma)}{(mR_n + \gamma\delta_e(1 + 0.536u_w))} \frac{P}{c_p\Delta T_p} \left[\frac{1}{1 + \frac{s_o}{\Delta s}} \right] \quad (m^2) \quad (26)$$

B. Salinization by dumping salt into the seawater

Let us consider the second method, in which salinity enhancement is attained by pouring salt directly into the seawater. The salt could be transported by a tug-boat, for example, from a nearby onshore repository of saline brine. This option is clearly attractive for locations near salt flats.

Proceeding as before, we first define our salt mass balance, depicted in Fig. 6, with

$$\frac{\dot{m}_s\Delta t + \dot{m}_{si}\Delta t}{\dot{m}_w\Delta t} = \frac{\dot{m}_{so}\Delta t}{\dot{m}_w\Delta t} \quad (27)$$

where $\dot{m}_s$ is the mass flow of salt initially dissolved in the water; $\dot{m}_{si}$ is the injected mass flow of salt (the salt input); $\dot{m}_w$ is the mass flow of seawater; $\dot{m}_{so}$ is the final mass flow of salt; and Δt is the time interval. Knowing that $\frac{\dot{m}_{so}\Delta t}{\dot{m}_w\Delta t} = s_2$, i.e., the final required salt concentration, and $\frac{\dot{m}_s\Delta t}{\dot{m}_w\Delta t} = s_o$, i.e., the initial salinity, Eq. (27) may be rewritten as

$$\dot{m}_{si} = \dot{m}_w s_o \frac{\Delta s}{s_o} \quad (28)$$

Using Eq. (9), this becomes

$$\dot{m}_{si} = \frac{s_o P}{c_p \Delta T_p} \frac{\Delta s}{s_o} \quad (29)$$

and considering Eq. (14) yields

$$\dot{m}_{si} = \frac{s_o P}{c_p \Delta T_p} \left[\frac{16fP^2}{\pi^2 \rho D^5 g s_o c_p^2 \Delta T_p^2 \nabla_s \rho} + \frac{\Delta T \nabla_T \rho}{s_o \nabla_s \rho} \right] \cdot \frac{1}{\Psi_{s_o}} \quad (30)$$

IV. RESULTS AND DISCUSSION

To obtain some idea of the shape of the curves predicted by Eq. (20), Eq. (26) and Eq.(30) for the required evaporation rate, salinization by solar evaporation and salinization by dumping salt into the seawater, respectively., we assume some typical parameter values: $T_a \sim 298$ K; $m \sim 0.18$ kPa/K; $\lambda_v = 2.2$ MJ/kg; $e_r \sim 0$ (assuming continuous removal of vapor and then maximum evaporation); $\delta_e = e_s$ with $e_s \sim 3$ kPa; $u_w \sim 3$ m/s; $\gamma = 7.4 \times 10^{-2}$ kPa/(K) for an atmospheric pressure of 100 kPa; $c_p = 4.2 \times 10^3$ J/(kg)(K); $\Delta T \sim 20$ K. The resulting curves in Fig. 6. Fig. 6a is the required evaporation rate as a function of the power plant, and Fig. 6b the dedicated area of evaporation as a function of the power plant for clear and cloudy days. It is easy to see that power plants of up to 1.0 MW are practical using reasonable dedicated evaporative areas of up to 10^4 m^2 .

On the other hand, the curve predicted by Eq. (30) is shown in Fig. 7.

In this figure, it can be seen that a 100 kW power plant will require 2 kg of salt to be added to the seawater per second, a total of 172 tons per day.

Note that, because the concentrated flow is diluted by water moving across the semipermeable membrane, the mass flow rate of the cold stream to the power plant is larger than the mass flow rate of the concentrated flow coming into the membrane module.

However, this additional flow has been deliberately neglected because the PRO process includes the generation of additional hydraulic pressure introduced in Eq. (6). Indeed, for the PRO process, a fraction of the flow resulting from the mixing must be bifurcated into a stream that flows through the PEX to transfer pressure to the incoming draw (high concentration) flow. It has been demonstrated that the PEX requires a flow that is approximately equal to that leaving the mass exchanger [14], and so it can be assumed that the mass flow rate of the cold stream is equal to the mass flow rate of the concentrated flow coming into the membrane module.

A. computational simulation

To simulate the salinity-induced convection and FO through a semipermeable membrane, we used the FLUENT [22] computational fluid dynamics (CFD) software. FLUENT has comprehensive modeling capabilities

FIG. 6: **a)** Required evaporation rate as a function of the power plant. **b)** Dedicated area of evaporation as a function of the power plant and some values of solar irradiance.

FIG. 7: Required salt rate as a function of the power plant.

for a wide range of compressible/incompressible, laminar/turbulent fluid flow problems. Its ability to simulate convection driven by salinity gradients has been extensively demonstrated and experimentally validated in solar pond operations [23], [24] as well for FO through semipermeable membranes [15], [25], [26]. In application to our OTEC study, as the characteristic length-scale of the system ranges from tens to hundreds of kilometers, it would be computationally expensive to perform a full-scale CFD simulation. Indeed, the simplicity of the problem makes this unnecessary, as we are essentially assessing the feasibility of inducing a flow between two columns driven by differences in densities (because of dif-

ferent salinities) and the desalination process occurring in between at the mass exchanger (under FO).

With this goal in mind, a 2-D model composed of two chambers (top and bottom) was simulated (see Fig. 8). The dimensions are similar to those used in [26], with $a = 60 \text{ mm}$, $b = 25 \text{ mm}$, and width 75 mm . The height of the upper chamber is $h = 25 \text{ mm}$. It is preferable for the simulation of the boundary between the top and bottom chamber, which represents the semipermeable membrane, to use a cell zone definition, as suggested by [26], rather than a user-defined function (UDF) or source term adjustment for the FO process, as in earlier studies. Therefore, the boundary condition was treated as a porous zone and the porosity of the membrane was set to 0.05% [26]. The full geometry was discretized into small control volumes using a Gambit mesh generator with 192100 elements.

The boundary conditions (left, top, and right) were set as follows:

$$P_1 = \rho_1 g H \quad ; \quad \text{*left boundary condition}$$

$$P_2 = \rho_2 g H \quad ; \quad \text{*right boundary condition}$$

$$P_o = \rho_o g (H - h) \quad ; \quad \text{*top boundary condition} \quad (31)$$

where ρ_1 is the density of the seawater column after salinization, H represents the height of the column, which was set to $H = 1000 \text{ m}$, and g is the gravity. For the right boundary, the density ρ_2 was not fixed to ρ_1 , but was calculated using a UDF [22] in each computational step. This density corresponds to the desalinated water

resulting from the mixing at the mass exchanger. Finally, the density ρ_o was held constant as the average density of the column of water. The height h was used to allow a better representation of the porous zone between both chambers. The salt concentration in the top chamber was set to 35 ppm, and that of the salinized stream (coming from the left side) was set to 66500 ppm.

From the simulation, an average steady flux *left* $\rightarrow$ *right* was obtained as 8.55×10^{-5} m/s.

V. CONCLUSIONS

The possibility to run an OTEC plant by the deliberate salinization of surface seawater has been discussed. In this technique, and contrary to traditional OTEC technology, instead of bringing bottom cold water to the surface (by using pumps), here the warm surface water is circulated to the bottom, cooled there, and lifted back to the surface and being the entire process driven by an induced salinity gradient at the surface. The main findings raised by this study are as follows:

- (a) It is quantitatively possible to run an OTEC plant of up to 1.0 MW using a practical, realizable evaporative area of around 10^3 - 10^4 m².
- (b) Pouring salt directly into the seawater would appear to be limited to power plants of up to 100 kW, which would require the addition of 172 tons of salt per day.

NOMENCLATURE

A_s = area of evaporation, m²
 c = molar concentration, mol/ m³
 c_p = heat capacity J/(m³)(K)
 D = diameter of the pipe, m
 e_s = saturated vapor pressure, kPa
 e_a = vapor pressure of free flowing air, kPa
 δ_e = vapor pressure deficit, kPa
 f = nondimensional friction factor
 g = gravity, m/s²
 H = OTEC depth, m
 L = total pipe length, m
 m = mass, kg
 $\dot{m}$ = mass flow rate, kg/s
 $\dot{m}_{we}$ = mass flow rate of evaporation, kg/s
 $\dot{m}_w$ = mass flow rate of seawater, kg/s
 $\dot{m}_{w2}$ = mass flow rate of salinized seawater, kg/s

$\dot{m}_s$ = mass flow rate of salt (diluted into the seawater), kg/s
 P = power, W
 p = pressure kPa
 R = the gas constant, J/(K)(mol)
 R_p = radius of the pipe, m
 R_n = solar irradiance, MJ/(m²)(day)
 s = salinity, %
 T = temperature, K
 T_a = air temperature at surface of seawater, K
 T_c = cold (bottom) temperature of seawater, K
 T_h = hot (surface) temperature seawater, K
 $\Delta T = T_c - T_h$, K
 $\Delta T_p = T_h - T_c$, K
 Δt = time, s
 v = velocity, m/s

Greek symbols

ϵ = PRO efficiency
 ρ = density of seawater, kg/m³
 ρ_o = nominal density of seawater, kg/m³
 ρ_2 = density of seawater after salinization, kg/m³
 ρ_1 = density of water at nominal salinization at the bottom of the sea, kg/m³
 γ = psychometric constant, kPa/K
 λ_v = latent heat of vaporization, MJ/kg
 Π = osmotic pressure, Pa
 Ψ_{so} = nondimensional osmotic pressure factor

subscript symbols

o = nominal, reference
 c = cold
 h = hot
 hx = exchanger
 1 = cold, bottom seawater
 2 = hot, salinized seawater

ACKNOWLEDGEMENTS

This research was supported by the Spanish Ministry of Economy and Competitiveness under fellowship grant Ramon y Cajal: RYC-2013-13459.

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FIG. 8: Geometry used for the analysis.

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