Pool Pressure-Retarded Osmosis

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In this work, consideration is given for pressure -retarded osmosis (PRO) system in a pool configuration. The motivation behind of such a configuration lies in the possibility to eliminate mechanical moving parts or energy recovery systems -as for example pressure exchangers (PEXs), which are needed in traditional PRO systems. In a pool configuration mobil parts as pumps or PEXs may no longer be needed because advantage is taken not only in the osmotic energy released upon the mixing of the two solutions with different concentrations but also in the buoyant potential from the gradient of density. The preliminary mathematical development for a pool configuration constitute the core of this work. The main theoretical difficult which aroused when attempting to analyze a pool-PRO system was the determination of the vertical motion of the plume formed immediately after the detachment and the mixing which must be at least equal than that given by the water permeability coefficient of the membrane if it is desired that the system works in a steady stay. Because hydrodynamic entrainment induced by the vertical motion of the plume must be promoted in order to replenish with fresh draw solution the membrane, then it must be arranged in clusters which from computational fluid dynamics CFD simulations performed should be in the range of 50 to 100μm.

Keywords. *Pressure-retarded osmosis (PRO); Membrane permeability Coefficient, Osmotic energy; buoyancy*

I. INTRODUCTION

The huge potential of harvesting energy from salinity gradients has been debated for almost 50 years, however, interest has reawakened in the last years owing to the research progress in the design of new more effective membranes [1],[2]. Several technologies have been researched to extract energy from salinity gradients,[3], but doubtless pressure-retarded osmosis (PRO) is the technique which has emerged as the most promising technology, [4]. Although many configurations for a PRO system have been proposed, for example, concepts in which osmotic power production is attained by pressurizing the fluid rather than increasing volumetric flow, [5], or concepts related with the design of the module configuration of the PRO membrane, [6] as well as alternative applications,[7],[8], however, for illustration purposes, the most simple PRO system depicted in Fig. 1 seems preferable. [9]. In this figure, a high concentration solution -generally referred as the draw, is propelled by the pressure exchanger (PEX) which transfer osmotic pressure generated at the membrane module. At the same time the low concentration solution -generally referred as the feed, is pumped at room pressure into the opposite side of the membrane module. In the membrane module water molecules coming form the feed permeate to the draw stream and then increasing the flow rate and diluting the pressurized draw while concentrating the feed stream.

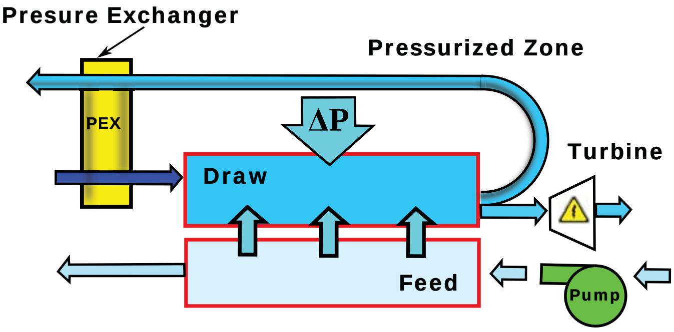

FIG. 1: Sketch of a traditional PRO configuration.

The object of this work was a first assessment for a pool-PRO system in which the diluted draw is pulled away from the membrane by action of its own buoyancy and then offering a new alternative to the classical use of PEXs. In summary, the paper deals with the possibility for a PRO system in which advantage is taken simultaneously of the osmotic potential energy released during the spontaneous mixing of the two solutions with different salinities as well as the resulting buoyant potential.

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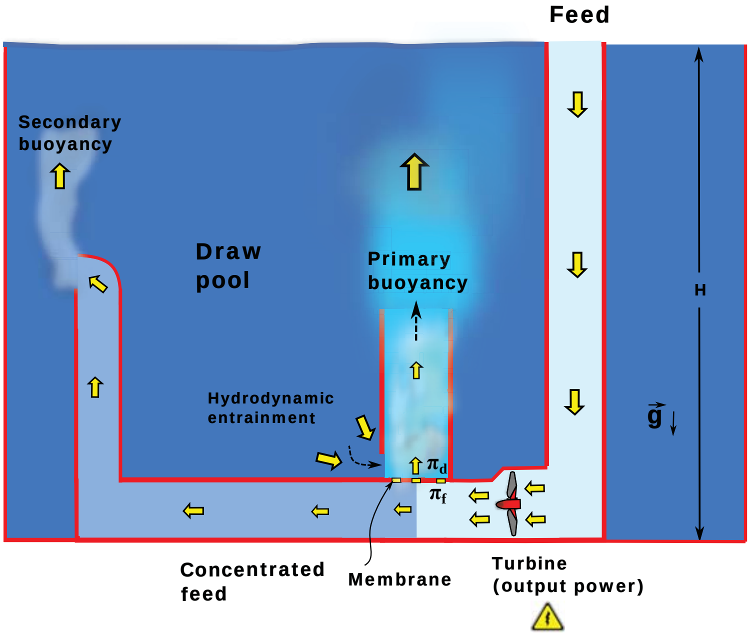

FIG. 2: Sketch of a possible pool PRO system.

II. MATERIALS AND METHODS

A. Statement of the core idea

To begin with, let us consider the most general configuration for a hypothetical pool-PRO system as depicted in Fig. 2. From this figure and unlike to the traditional approach (see Fig.1), there are neither pressure exchangers nor pumps and instead both the diluted draw as well as the concentrated feed are pulled away by buoyancy. According with Fig. 2, in order to run the system in a steady-state, the only critical point is that the buoyant plume (primary buoyancy) pull the diluted draw at the same velocity as it is formed, i.e., at the same rate of the osmotic flux given by the membrane (specifically by the water permeability coefficient of the membrane). The motion of this plume is difficult to solve analytically, even if hydrodynamic entrainment is omitted, however, a preliminary insight can be gained by using the bubble theory for jets and plumes, which is pictorially depicted in Fig. 3.,[10], where an idealized convective bubble ascendent bubble is shown. Within the framework of the bubble theory -and based on dimensional analysis, it is argued that the vertical velocity v_b of a bubble just at the initial moment when is starting its vertical motion is given by

$$v_b = B\left[\frac{4gd}{3}\right]^{\frac{1}{2}}\left[\frac{\rho_D-\rho_F}{\rho_F}\right]^{\frac{1}{2}} \tag{1}$$

where B is a dimensionless constant to be determined theoretically or experimentally, g is gravity; d is the diameter of the semi-spherical cap of the plume which can be approximated to the size of the membrane; and ρ_D and ρ_F are the density of the draw and the feed, respectively.

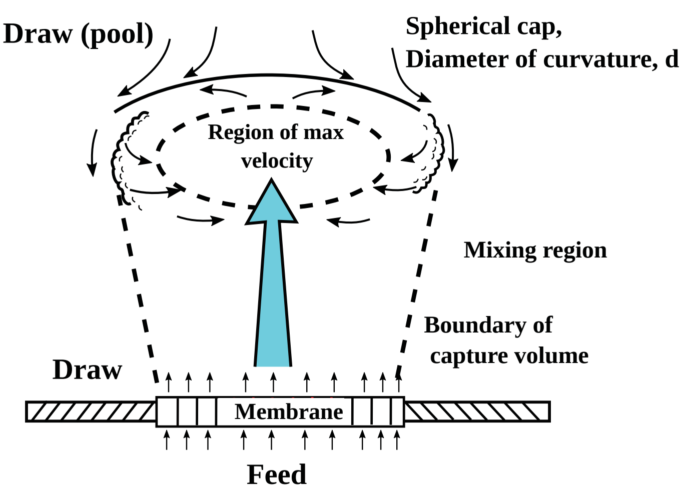

FIG. 3: Structure of an idealized convective bubble, derived from [10]

It is convenient to express the gradient of densities in Eq.(1) as function of the gradient of concentrations. The variation of the density with concentration c fir very well with a linear function

$$\rho(c) = \rho_o + \frac{\partial\rho}{\partial c}c \tag{2}$$

where ρ_o is the reference density when $c = 0$. Therefore the term $\frac{\rho_D-\rho_F}{\rho_F}$ can be rewritten as

$$\frac{\rho_D-\rho_F}{\rho_F} = \frac{\frac{\partial\rho}{\partial c}(\Delta c)}{\rho_o + \frac{\partial\rho}{\partial c}c_F} \tag{3}$$

which considering $\rho_o \gg \frac{\partial\rho}{\partial c}c_F$ simplifies as

$$\frac{\rho_D-\rho_F}{\rho_F} = \beta\Delta c \tag{4}$$

where a concentration coefficient of density was defined as

$$\beta = \frac{1}{\rho_o}\frac{\partial\rho}{\partial c} \tag{5}$$

Inserting Eq.(4) into Eq.(1) yields

$$v_b = B\left[\frac{4gd\beta}{3}\right]^{\frac{1}{2}}\Delta c^{\frac{1}{2}} \tag{6}$$

From Eq.(6) the vertical velocity depends on the diameter of the semi-spherical cap, d, which for a plume starting its vertical motion is approximately equal than the the size of the membrane cavity. Now, according with Eq.(6) one may be tempted to think that because it is desired that the buoyant velocity of the plume be as higher as possible -and then making the membrane the only limiting factor for the osmotic flow, then by increasing the size of the membrane, i,e., d, we can increase the velocity of the plume as we please. However, it is not the case. In fact, the system works only in so far as new fresh draw solution is renewing the diluted draw solution formed just above the membrane, and then keeping the difference of salinity between both sides of the membrane. The continuous "refueling" of new draw solution in the membrane can be only possible because the hydrodynamic entrainment induced by the buoyant vertical motion of the plume as is shown in Fig. 3. This hydrodynamic entrainment is originated by the detachment of the plume and not by its velocity vertical velocity per se. Therefore, if we consider in Eq.(6) that the vertical velocity depends on the dimension d as $v \propto d^{\frac{1}{2}}$, and then one would expect a frequency of department or detachment of the plume f in the order of $f \approx \frac{v}{d} \approx d^{-\frac{1}{2}}$ (i.e., larger plumes-caps taking longer to grow and to detach). This seems in good agreement with semiempirical correlations combining bubble departure diameter and frequency for vapor bubbles where general form of correlations is

$$f d^n = C \tag{7}$$

where c is a constant, and values of n between $\frac{1}{2}$ and 3 have been suggested, as for example, Jakob (1949),[11] with $n = 1$ or Ivey (1967),[12] with $n = 2$ when bubble growth is dynamically controlled.

By aforementioned, the membrane grid cannot be a continuous porous media but instead arranged into clusters with a certain size as pictorially shown in Fig. 4, and it is desired that each cluster be as small as possible (and the favoring hydrodynamic entrainment by increased frequency of departure of the plume) but large enough in order that the plume attain a vertical velocity equal that that given by the water permeability coefficient.

The velocity given by the water permeability coefficient of the membrane may be calculated as follows. First, the water flux across a membrane J_w (volume per unit of time and area of membrane) is given by, [13]

$$J_w \approx A(\Delta\pi - \Delta P) \tag{8}$$

where A is the membrane water permeability coefficient; $\Delta P = gH(\rho_{-}\rho_F)$ and $\Delta\pi = \pi_D - \pi_F$ are the hydrostatic and total osmotic pressure and the subscripts D and F stand for draw and feed, respectively.

Because for the most practical applications the total osmotic pressure will be much more higher than the differential hydrostatic pressure between the draw and feed columns, i.e., $\Delta\pi \gg \Delta P$ and if the membrane has a surface s_m the total volumetric flow is $Q_m = J_w s_m$ and the flow velocity yields

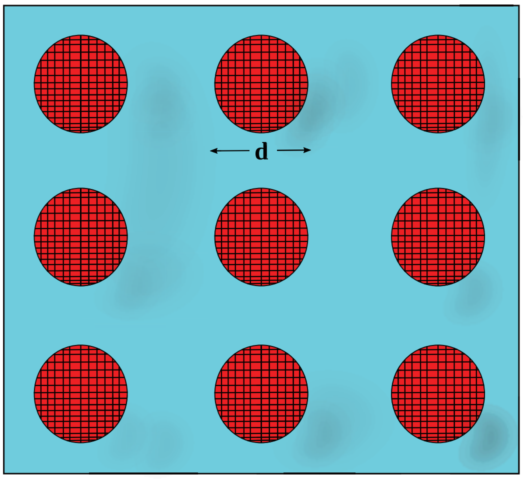

FIG. 4: Clustering of the membrane porous media in order to facilitate hydrodynamic entrainment and removal of the mix.

$$v_m \approx A(\Delta\pi) \tag{9}$$

On the other hand, the osmotic pressure is a function of the molar concentration following the van´t Hoff equation

$$\pi(c) = \nu R T c \tag{10}$$

being ν the van´t Hoff factor; R is the ideal gas constant, and T is the absolute temperature. Thus, taking into account Eq.(10), Eq.(9) becomes

$$v_m \approx A(RT\nu\Delta c) \tag{11}$$

where $\Delta c = c_D - c_F$ is the difference in molar concentrations between the draw and the feed, respectively.

By equating the buoyant velocity, Eq.(6), with the osmotic velocity, Eq.(11), one obtains the require dimension of the cluster d

$$d = \frac{3EA^2R^2T^2\nu^2\Delta c}{4g\beta} \tag{12}$$

where E is a dimensionless constant to be determined experimentally or from computational simulations.

Although Eq.(12) allow us to identify the many parameters involved, however, it is true that the model assumes that the plume is almost shape-preserving, i.e., to have a form which maintains geometrical similarity during much of their development, and this approach leads to important overestimation in the calculations, because inasmuch that the buoyant element ascends mixing is expected to take place through its boundaries, and this dilution by mixing will tend to reduce the buoyancy.

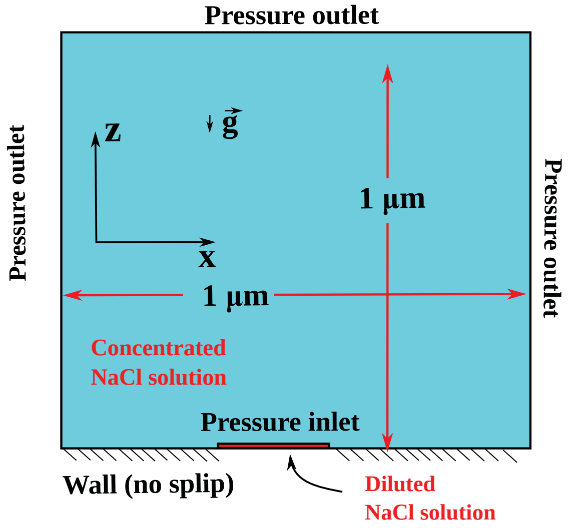

FIG. 5: Geometry for numerical simulation. Schematic depicting the geometry and the boundary conditions used in FLUENT Ansys ® Software.

B. Computational simulation

In order to obtain some estimate for the velocity of detachment of the plume, computational fluid dynamics CFDs simulations were performed using the Ansys Fluent CFD software version 14.

- **Problem description:**

The problem to be considered is shown schematically in Fig. 5 and the objective was basically to obtain the velocity of a plume of mixed material immediately is released into a pool as function of the dimension of the cavity d. With such a goal, a series of simulations were performed in which a given NaCl solution (the feed) was allowed to enter into a pool of another NaCl solution but with a higher concentration (the draw pool). The geometry was a simple square box 1000μm $\times$ 1000μm with a centered cavity with dimension d which was a variable parameter. The Analysis was performed with presto-pressure discretization, and relaxation factors as assumed by default. Convergence criterion was set for 10^{-3} for momentum and continuity as well. Water properties were assumed as constant with $\rho = 10^3$ kg/m^3; $\mu = 10^{-3}$ Pas and a constant temperature $T = 300$ K. The mixture multiphase option was the choice.

III. RESULTS

The resulting curves for the velocity of the plume during the detachment the cavity as a function of Δc and for some dimensions of the cavity d are shown in Fig. 6. It is seen that the membrane should be arranged in clusters with dimensions near to 100 μm.

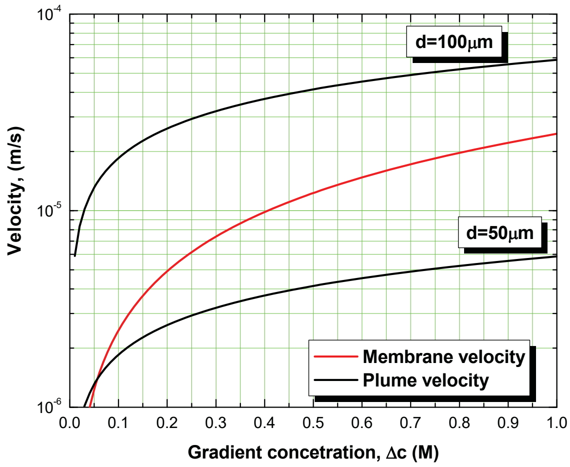

FIG. 6: Velocity of the plume for a range of sizes of the module and the velocity given by the permeability of the membrane.

IV. CONCLUSIONS

In this work, consideration was given for pressure - retarded osmosis (PRO) system in a pool configuration in which the diluted draw is pulled away from the membrane by action of its own buoyancy. It was found that clustering could be required to continuously propel the diluted draw by the induced hydrodynamic entrainment from the vertical motion of the plume. Pool configurations will require minimum maintenance in comparison with traditional PRO systems because the suppression of PEXs or other energy recovery systems and then having an impact in the economy. Pool-PRO configuration could be specially attractive when large volumes of solutions are available, as for example in oceans and river waters (blue energy). Additional R&D is required in order to arrive at a reliable practical and commercial design.

NOMENCLATURE

A = water permeability coefficient
B = constant
c = concentration
C = constant
d = diameter of the porous or cavity
E = constant
f = departure frequency
g = gravity
J = water flux across the membrane
P = pressure
R = ideal gas constant
T = temperature
v = velocity

Greek symbols

π = osmotic pressure
ν = the van´t Hoff factor

$\beta =$ concentration coexistent of density
$\rho =$ density

subscripts

$D =$ draw
$F =$ feed
$m =$ mixture, membrane
$o =$ reference

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