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A first estimate for a pressure retarded osmosis-driven thermosyphon

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ABSTRACT

Pressure retarded osmosis (PRO) process and its significance for thermosyphon technology is discussed. In previous work the possibility to drive a thermosyphon by difference of densities from induced salinity gradients from evaporation at solar collectors with downward heat transfer was assessed. Nevertheless it was concluded that large evaporative areas or dilution with volatile compounds was mandatory. In this work it is shown that by taking advantage of the energy released during the spontaneous mixing of the low-concentration evaporative fraction and the high-salinity of the no-evaporated fraction which is generally referred as pressure-retarded osmosis (PRO) process, then the thermosyphon can runs with downward heat transfer (hot fluid flows down and cold fluid rises up) and using an evaporative surface area much more smaller and then eliminating the need for dilution with high volatile compounds.

1. Introduction

In a recent work the possibility to drive a thermosyphon by salinity gradients rather than traditional thermal gradients and then with downward heat transfer as alternative to the traditional upward heat transfer thermosyphon was assessed (Arias and de las Heras, 2017). In that approach, evaporation is promoted at the solar collector and as a result, the no-evaporated fraction with an increased salinity, and density, than the evaporated fraction sinks. The resulting downward heat transfer may be particulary attractive for domestic solar applications if one considers that solar energy is generally collected at the roofs and then needs to be transported inside houses. Unfortunately, to do this, the required surface area of evaporation was found too large if pure water was used, and then the dilution with a high volatile compound was mandatory.

In this work it is demonstrated that the salinity gradient form the induced evaporation could be harnessed in a better way, not by buoyancy (difference of densities) but for taking advantage of the energy released during the spontaneous mixing of the low-concentration evaporative fraction and the high-salinity of the no-evaporated fraction, in a process generally termed as pressure-retarded osmosis or PRO process.

Whereas osmosis has been researched for several solar applications (Khayet et al., 2016; Arias, 2017b,a; Schrier, 2012; Carta et al., 2003; Infield, 1997; Carlsson et al., 2016; Kalogirou, 2009), nonetheless, the PRO process has received a very limited study for solar applications. e.g., for increasing solar pond efficiency (Bemporad, 1992).

1.1. Pressure retarded osmosis

In short, pressure retarded osmosis or PRO process, is the technique based in harvesting the energy released during spontaneous mixing of two solutions with deferent salinities (Israel Patent Application 42658, 1973). The PRO process, since the 1970s, has been considered mostly as a sustainable energy source to desalination systems, or commercial power plant generation from the mixing of seawater and rivers or wastewaters with lower salinity. Unfortunately, it has been found, among other problems, that biofouling (or bacteria that clog the membrane structure and the feed channel) in those systems is of critical importance in reducing power generation next to nothing.

Although, it is certain that biofouling cannot be controlled -or at least economically controlled, in huge open-loop seawater systems where massive amounts of water are involved, nonetheless, this problem is not present in very small, compact and recirculating systems as could be a domestic thermosyphon where the extractable energy must be just enough to propel the fluid downward and overcoming the buoyancy as well friction losses.

2. The pressure retarded osmosis-driven thermosyphon

2.1. Momentum and thermodynamic considerations

To begin with, let us consider, for illustrative purposes, a possible pressure retarded osmosis-driven thermosyphon as schematically depicted in Fig. 1. Referring to this figure, a fluid loaded with a certain salinity (aqueous solution) is circulating in a closed-loop thermosyphon

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Nomenclature

A_s	area of evaporation
c_D	high-salinity concentration (draw)
c_F	low-salinity concentration (feed)
c_M	salinity mixed concentration
c_p	heat capacity
D	diameter of the pipe
e_s	saturated vapor pressure
e_a	vapor pressure free flowing air
δe	vapor pressure deficit
f	friction factor
g	gravity
ΔG_v	Gibbs energy per volume
L	length of the pipe
m	slope of the saturation vapor pressure curve
$\dot{m}$	mass flow rate
$\dot{m}_e$	mass flow rate of evaporation
$\dot{m}_w$	mass flow rate of water
p	pressure
R_n	solar irradiance
s	salinity %
T	temperature
T_a	air temperature
T_c	cold temperature
T_h	hot temperature
ΔT	$T_h - T_c$
u_w	wind speed
W	power

Greek symbols

η	PRO efficiency
ϕ	feed (low-salinity) volume fraction
Π	osmotic pressure
ρ	density of seawater
γ	psychometric constant
λ_v	latent heat of vaporization
∇	gradient
Δ	difference

Subscripts symbols

o	nominal, reference value
c	cold
h	hot
π	osmotic

system. We assume water with a reference density ρ_o and salinity s_o (in % weight of salt). Then, after passing through the collector and being heated, some fraction is evaporated resulting in two streams with differences salinities. Let us call the low-salinity evaporated fraction with concentration s_1; and the high-salinity no-evaporated fraction with concentration s_2. Then both solutions are brought together and mixed (by using a proper semi-permeable membrane) and then the final mixture recovers its initial salinity s_o but with a temperature $T_h$higher than the initial temperature T_c before passing through the solar collector. From the mixing of two stream with different salinities, it is obtained an extractable energy from a PRO process which can be transformed as hydrodynamic pressure by means of a pressure exchanger (PEX) (Lin et al., 2014). This although rather simplified scheme, is nonetheless outlining the fundamental basis of a pressure retarded osmosis-driven thermosyphon, and from this simplified scheme, a first theoretical treatment can be developed as follows.

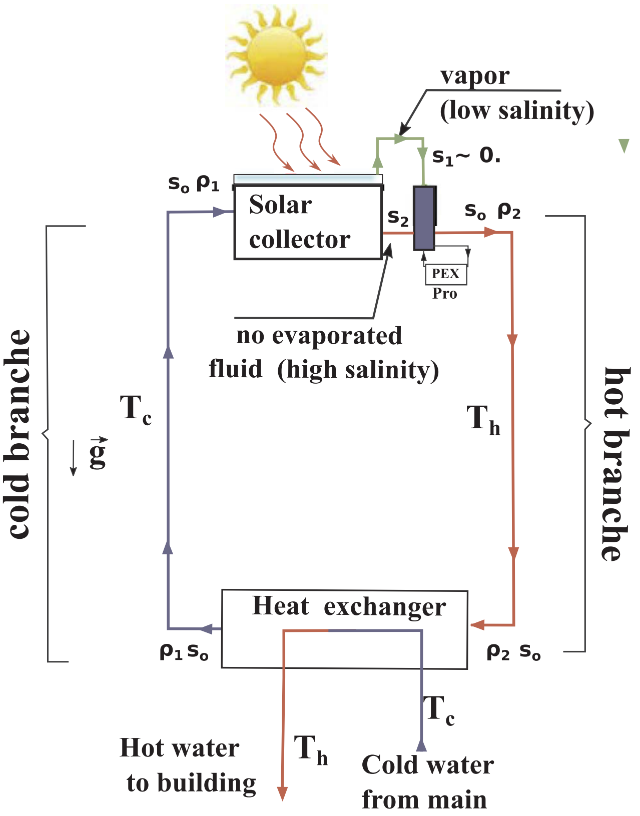

Fig. 1. Physical model for analysis of the *osmotic thermosyphon*.

First, after the fluid is heated at the evaporator, there would be two streams as schematically depicted in Fig. 1. In the no-evaporated fraction, the salinity is increased from the initial value s_o to s_2 and its temperature rises from T_c to T_h as a result, its density changes as

$$\rho_2 = \rho_1 + \nabla_T \rho \Delta T \tag{1}$$

where

$$\Delta T = T_h - T_c \tag{2}$$

and $\nabla_T \rho$ is the gradient of density with temperature, which for water thermosyphon temperatures is always negative, i.e., the water becomes lighter after passing through the collector. On the other hand we have the evaporated stream, which is depleted in salt and with a salinity s_1. For our purposes, it is allowable to assume that $s_1 = 0$. Also its temperature is in thermodynamic equilibria with the no-evaporated stream and then is at T_h

Finally, both streams with different salinities are mixed, and then an osmotic pressure Δp_π can be obtained by a PRO process (Lin et al., 2014; Loeb and Norman, 1975; Straub et al., 2016; Wang et al., 2016). The condition here investigated is if this pressure could overcomes the buoyancy plus the friction losses and then propeling the hot water through the entire system. Mathematically this condition implies

$$\Delta p_\pi > \frac{8fL\dot{m}_w^2}{\pi^2 \rho D^5} + (\rho_1 - \rho_2)gH \tag{3}$$

where the first term is the pressure friction losses and the second one the hydrostatic buoyant pressure, being H the effective height of the pipes, g is gravity L is the total pipe length, f the pipe friction coefficient, $\dot{m}_w$ the water mass flow, D the diameter of the pipe, ρ the average density of the fluid. By using Eqs. (2) and (3) may be rewritten as