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Solar-driven thermo-hydraulic process for reverse osmosis desalination

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Abstract:

Existing distillation-based desalination processes are highly thermal energy consuming. Reverse osmosis (RO) technique is more efficient than thermal-based processes but it remains a solution that still induces high operating and maintenance costs. In this paper, an innovative thermally powered RO-based desalination process is presented. This new RO thermo-hydraulic process enables the pressurization of the salty water beyond its osmotic pressure to allow the permeation water through a semi-permeable membrane, thanks to a piston or an elastic bladder that is set in motion in a reservoir by a working fluid following a thermodynamic engine cycle similar to an Organic Rankine Cycle. The evaporator is heated by low grade heat (70 to 80°C) such the one delivered by plate solar collectors, while the condenser is cooled by the concentrated salty water. In order to enable a continuous drinkable water production, this process needs to implement two reservoirs, alternatively connected either to a high pressure evaporator or to a low pressure condenser. Such installation, designed here for brackish water desalination (5 g/liter), should enable an average daily production of 300 liters of drinkable water per m² of solar collectors with a production cost below 4€/m³. That technology seems to be relevant for small scale (5 to 10 m³/day) the daily water needs of people living in remote areas, in accordance to the location and the solar resource. A modeling of the whole process, considering a quasi-steady state approach has been developed in order to study its dynamic behavior, optimize its design and maximize its performances. This paper presents the preliminary results relative to the performance of such solar-driven desalination process.

Keywords:

Solar desalination, thermal energy, reverse osmosis, thermo-hydraulic cycle, dynamic modeling.

1. Introduction

Growth of the demand in seawater and brackish water desalination over the past years is motivated by the increasing water stress in more and more countries. Even if the major part of desalination systems is powered by fossil energies, desalination systems driven by renewable energies are now well known and available on the market. Solar desalination is particularly interesting considering the most water lacking areas have an important sun resource.

Solar driven desalination can be led by two different ways: distillation or membrane separation. In solar distillation systems, the water is evaporated by the solar heat. The most current distillation based technologies are the multi-effect distillation (MED) and the multi-stage flash distillation (MSF). Those processes have a specific energy consumption (SEC) commonly ranging between 30 and 80 kWh of thermal energy per m⁻³ of produced drinking water [1].

Membranes-based desalination consists in separating the salt from water through a semi-permeable membrane. The most implemented membrane separation processes are electro-dialysis and reverse osmosis. In electro-dialysis processes, the salt is drained through an ion selective membrane by the way of two electrodes submitted to electrical potential. This process needs electrical energy to operate and leads to an energy consumption lower than 2 kWh_{elec}·m⁻³. This process is more appropriate for brackish water desalination with a salinity below 2 g/l [2].

Reverse osmosis (RO) enables to desalinate water with higher salinity through a semi-permeable membrane, thanks to the pressurization of the salty water beyond its osmotic pressure, which is proportional to the water salinity and temperature. Such a process needs mechanical energy to run, which is commonly provided by a high pressure electrical pump. The RO technology leads to specific energy consumptions ranging from 2 to 10 kWh_{mec}.m⁻³, and depending on the water salinity and temperature. This low energy consumption is obtained by recovering the mechanical energy of the pressurized concentrated water at the membrane output.

Distillation-based systems are easier to set up but their energy needs are higher than membrane-based technologies. Membranes-based desalination enables to obtain low energy consumption in comparison to distillation processes but they have some major operating issues, such as membrane deterioration or fouling, that lead to higher operating costs. Nevertheless, reverse osmosis is an interesting technology because of its low energy needs and its potential to be implemented at wide scale.

Exploiting solar energy via photovoltaic panels in order to produce electricity that is later converted into mechanical energy, implies the use of expensive mechanical energy conversion devices and electricity storage devices and leads to an important loss of efficiency. Solar heat-driven RO-based systems obtained by coupling a di-thermal power cycle with a membrane separation unit could be an interesting solution to avoid this energy conversion loss and obtain better installation efficiency. Manolakos et al. [3] studied and experimented such kind of desalination process by implementing an Organic Rankine Cycle (ORC), and obtained relatively good performances. With the same idea, a new likely process is investigated here in this paper. The new thermo-hydraulic process presented enables to use directly the expansion work of a fluid that follows a thermodynamic engine cycle, in order to pressurize the saline water in the RO unit. This solution enables to reduce importantly the energy conversion losses occurring during the mechanical work conversion and improves the global process efficiency. The process enables also to implement simple hydraulic and thermal components in order to be cost effective, easy to maintain, and to operate autonomously in off-grid remote areas by using low temperature solar heat provided by common flat plate solar collectors.

In this paper, such a new solar heat driven RO desalination process is described. A modelling of the whole process is carried out in order to evaluate its performance. The results are discussed in order to assess its relevancy.

2. System description

The thermo-hydraulic desalination process studied in this work and described Fig. 1 results from the direct coupling of a solar-powered Rankine-like engine cycle for the work generation with a reverse osmosis unit for the desalination. A set of two hydraulic cylinders are implemented for recovering the hydraulic energy of the brine flowing out the RO unit and making circulate the saline water in the process and the thermodynamic fluid of the engine cycle .

The engine cycle is mainly composed of an evaporator and a condenser. The evaporator, which is heated by the solar heat, generates vapors of the working fluid at high pressure. This vapor flows into a first reservoir that is filled with saline water and pressurizes it above its osmotic pressure. The condenser, which is cooled by the saline water to be desalinated, enables the condensation of the working fluid previously accumulated in a second low pressure reservoir.

The pressurization of the water in the tank is realized thanks to a free mobile piston set in motion by the vapor of the working fluid (Butane) that is produced at high pressure (approximately 15 bars) by evaporation in the evaporator of the thermodynamic cycle thanks to solar heat delivered by simple flat plate collector at about 70 to 90°C.

The hydraulic cylinders are set in movement thanks to the pressurized concentrated water flowing out of the RO module, recovering thus its hydraulic energy. A first hydraulic cylinder is used to pump and fill with water the low pressure reservoir and a second hydraulic cylinder is used to transfer the working fluid from the low pressure condenser to the high pressure evaporator. Each cylinder is composed of three chambers in order to make it behave in a symmetric way in both directions of movement, that is to say in order to ensure that the pumped and the pushed back volumes of water inside the chambers are equals. The pressurization is done in the middle chamber that contains the driving piston, which transmits the mechanical energy and set in movement the piston in the two lateral chambers in order to realize the pumping in a first step and backflow in a second step of the water to be desalinated, or the working fluid into the evaporator. Thanks to the first hydraulic cylinder, the feed water to be desalinated is firstly pumped at ambient temperature at a pressure just below the atmospheric pressure, then go through the condenser, acting thus as a cold source for the thermodynamic cycle and is temporarily accumulated in one of the lateral chamber of the hydraulic cylinder. Simultaneously, as the piston moves, the water to be desalinated, which was previously accumulated in the second lateral chamber of the hydraulic cylinder, is pushed out in order to fill the low pressure water tank connected to the condenser. At the same time, the water to be desalinated that is pressurized in the other tank by the high pressure vapor of the engine cycle, flows through the RO membrane. Clean water (permeate) is produced and the more concentrated water, which is still at high pressure, is used to drive the above mentioned hydraulic cylinders.

Several distributors and valves allow the role inversion of the reservoirs and the brine distribution in the process, as well as the control and the cycling of the different operating steps of the process. The retentate flow is controlled at the cylinders output by a constant flow rate valve, and regulating thus moving velocity of the cylinders pistons. All process elements requires to be salt-resistant.

2.1. Description of the operating cycle

The operating cycle of the process consists in several steps that are described in Fig. 1.

An initialization phase enables to put the feed tank, which is already completely filled with feed water, at the high pressure P_h by connecting the feed tank to evaporator. This high operating pressure level has to be preferably beyond two to three times the feed water osmotic pressure π to overcome transfer resistance throughout the RO membrane (see eq. (14))

The first step (Fig. 1a) consists in realizing the feed water desalination under ideally constant pressure. The high pressure feed water contained in the pressurized tank goes through the RO module and produces clean water. The still pressurized output brine is then used by the first hydraulic cylinder to pump the saline water and fill the second tank at the condenser pressure. The water filling of this tank discharges the vapors of the working fluid to the condenser where they condense at low pressure.

The second step (Fig 1b) is also a desalination phase, but under a decreasing pressure. The high pressure tank is disconnected from the evaporator, stopping supplying the tank with high pressure vapor. Then the pressure tank decreases until the osmotic pressure, enabling a decreasing clean water production to carry on until this point. At this step end, the second tank is completely filled with feed water that will be later desalinated and all of the working fluid previously contained in it has been expelled into the condenser.

As the pressure in the first tank becomes lower than the osmotic pressure (Fig. 1c), the remaining feed water cannot be desalted any longer. Nonetheless, this still pressurized water is used by a second hydraulic cylinder to transfer the liquid working fluid from the low pressure condenser to the high pressure evaporator. The vapor contained in this first tank depressurizes till the condenser pressure. At this point, a half-cycle has been achieved: the first tank is then fully filled with vapor and the second is full of feed water, both at low pressure, i.e. the working fluid saturation pressure

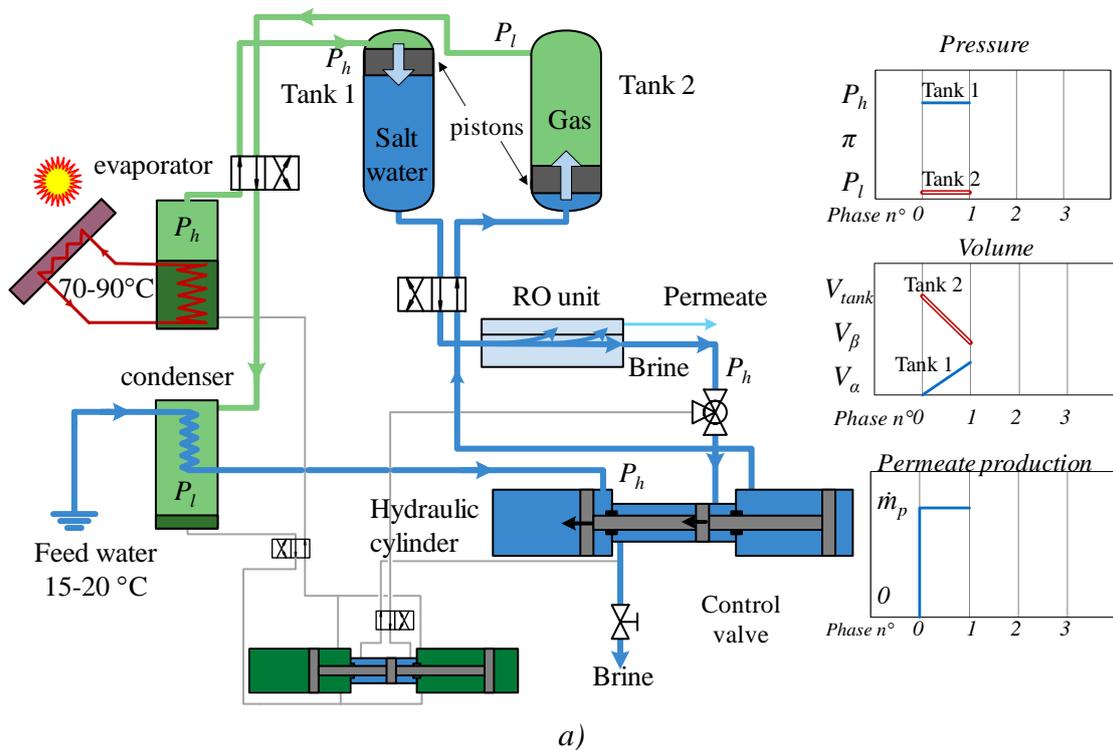
at ambient temperature. Distributors permit then to switch the tanks roles and run again a new half cycle.

Figures 1 represents the evolutions of the volumes of the vapor of the working fluid contained in the reservoirs V_α and V_β , V_{tank} . They respectively correspond the feed tank volume at the end of phase 1 (at high pressure P_h), the feed tank volume at the end of phase 2 (at osmotic pressure π) and to the fully filled tank volume (at low pressure P_l). An isentropic expansion of the working fluid has been considered in order to calculate these volumes (1) :

$$P_h V_\alpha^\gamma = \pi V_\beta^\gamma = P_l V_{tank}^\gamma, \quad (1)$$

The design of the hydraulic cylinders is currently led for optimizing the mechanical energy recovery. Their technology is under development in order to optimize the pumping depending on the energy recovered.

A first evaluation of the behaviour of this cyclic process is led here throughout a simple model. This modelling has been carried out by considering in first approximation a quasi-static operating mode, with the aim to first assess the process performances and its competitiveness by taking into account the variability of the solar resource and its cyclical operating.



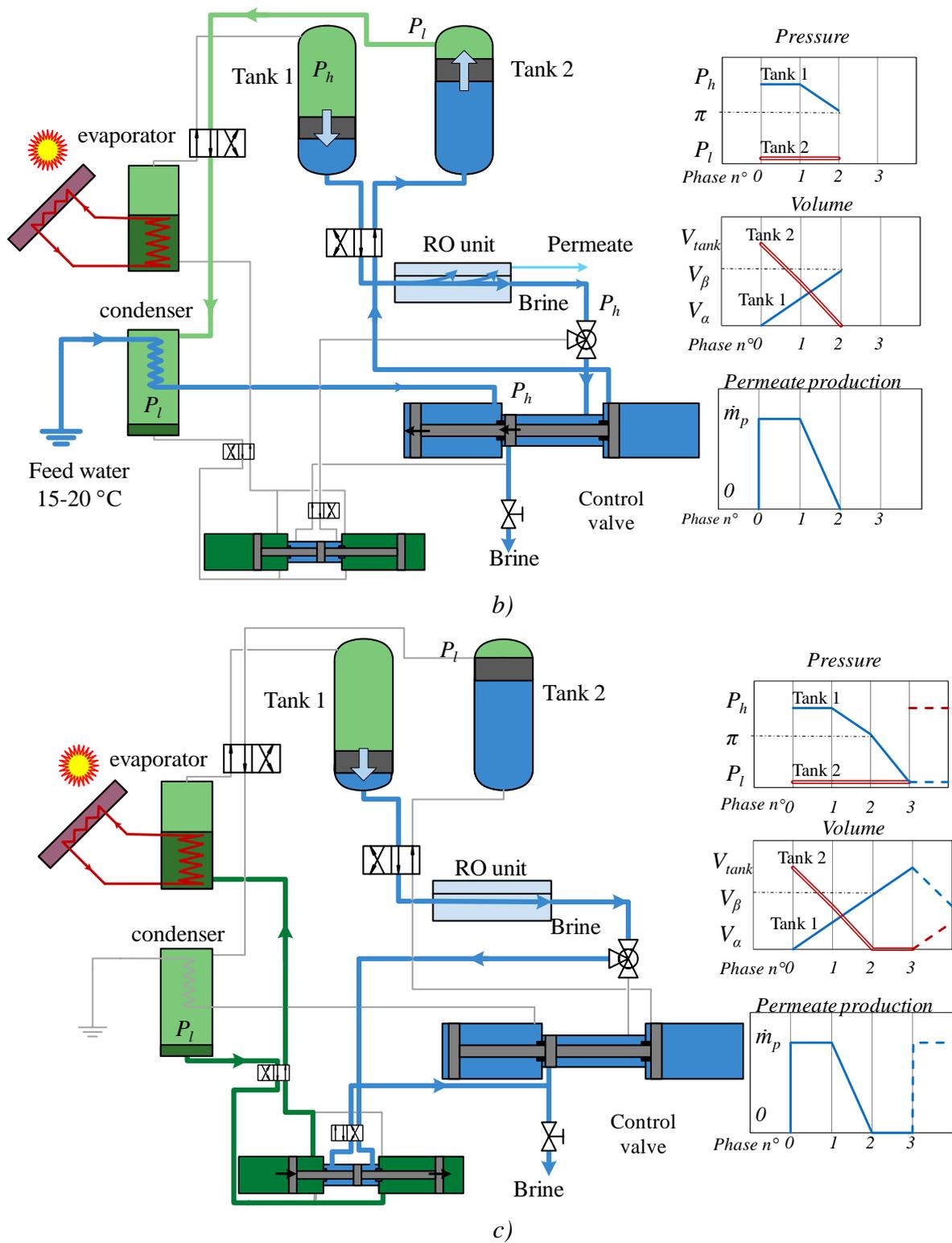


Fig. 1 : Representation of the different steps during a half-cycle process: a) phase 1 :desalination at constant pressure, b) phase 2 :desalination at decreasing pressure, c)phase 3 : working fluid transfer

3. Process modeling

The process behavior has been modeled by considering a nodal approach. All components of the system are assumed to be at a uniform temperature, pressure and concentration. The following mains assumptions have been considered:

- Thermal equilibrium between the liquid and gaseous phases in the evaporator and the condenser
- Frictions forces are negligible in the hydraulic cylinders and pipes
- Condensation effects are negligible in the tanks and pipes

3.1. Solar collector coupled to the evaporator

The evaporator of the system is heated by a heat transfer fluid circulating in a solar collector with a given mass flow rate, corresponding approximately to the commonly used value of 0.0139 kg/s.m².

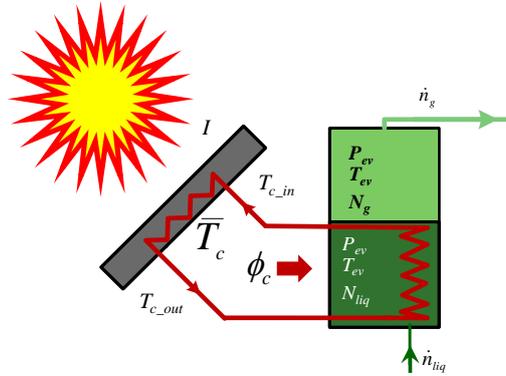


Fig. 2 : Solar panel and evaporator

The solar irradiation that is absorbed by the collector, of area A_c , and transmitted to the evaporator by the heat transfer fluid can be written as follows considering the collector efficiency:

$$\phi_c = IA_c \eta_c = \dot{m} C_p (T_{out} - T_{in}) \quad (2)$$

By taking into account an exchanger effectiveness value ε of 0.7 for the evaporator (3), the temperature difference of the heat transfer fluid can then be expressed in the equation (4) as a function of the collector average temperature \bar{T}_c and the evaporator temperature T_{liq} .

$$\varepsilon = \frac{T_{c_out} - T_{c_in}}{T_{c_out} - T_{liq}} \quad (3)$$

$$T_{c_out} - T_{c_in} = \frac{2\varepsilon_{evap}}{2 - \varepsilon_{evap}} (\bar{T}_c - T_{liq}) \quad (4)$$

The mean collector temperature \bar{T}_c is calculated iteratively by combining equations (2) and (4) and considering the commonly used expression for the collector efficiency η_c , which is a function of the optical efficiency η_0 , the mean fluid temperature and the solar irradiation,

$$\dot{m} C_p \frac{2\varepsilon}{2 - \varepsilon} (\bar{T}_c - T_{liq}) = IA_c \left(\eta_0 - \frac{a_1 (\bar{T}_c - T_{amb})}{I} - \frac{a_2 (\bar{T}_c - T_{amb})^2}{I} \right) \quad (5)$$

where a_1 and a_2 are respectively the linearly and quadratic thermal loss coefficients of the solar collector in W.m⁻².K⁻¹ and W.m⁻².K⁻².

Furthermore, the molar quantities of working fluid that are present in gaseous and liquid phase in the evaporator, can be obtained by considering energy and mass balances (6) and (7). An iterative procedure enables then to determine at each time step, the amount \dot{n}_{ev} of liquid that is evaporated in the evaporator.

$$\frac{dU_{ev}}{dt} = \phi_c + \dot{n}_{liq}h_{liq} - \dot{n}_g h_g \quad (6)$$

Where
$$U_{ev} = N_l C_{pl}(T_{ev} - T_{ref}) + N_g (h_g - RT_{ev}) + m_{ev} c_{v_wall_{ev}} (T_{ev} - T_{amb}) \quad (7)$$

$$\frac{dN_{liq}}{dt} = \dot{n}_{liq} - \dot{n}_{ev} \quad \text{and} \quad \frac{dN_g}{dt} = \dot{n}_{ev} - \dot{n}_g \quad (8)-(9)$$

The molar flow rate \dot{n}_g of the vapor that leaves the evaporator to the reservoir in order to pressurize the feed water is determined by the characteristics of the valve, i.e. its flow coefficient K_v , and the pressure difference existing then between the evaporator and the reservoir

$$\dot{n}_g = K_v \cdot \sqrt{P_{ev} - P_{res}}$$

A state equation for the working fluid is also considered in order to determine the pressure evolution in the evaporator and the pressurized reservoir, and then the pressure difference between these two components. The behavior of the working fluid vapor is in first approximation described by a virial equation of state (10):

$$\frac{PV_g}{N_g RT} = 1 + \frac{B(T)N_g}{V_g} \quad (10)$$

3.2. Transfer Tanks

The volumes V_f of saline water that is present in each transfer reservoirs are calculated thanks to a volumetric flow equation (11) knowing tank output mass rate of the feed water. The molar quantities of the gaseous working fluid in the reservoirs are also obtained throughout the molar balance (13). The polarity signs express the filling or emptying of reservoir with the saline water:

$$V_{res} = V_{g_Res} + V_f \quad (11)$$

$$\frac{dV_f}{dt} = \pm \frac{\dot{m}_f}{\rho_f} \quad \text{and} \quad \frac{dN_g}{dt} = \pm \dot{n}_g \quad (12)-(13)$$

3.3. Reverse osmosis module

The permeate flowing through the osmotic membrane is determined by the mass transfer equation (14) established by Lonsdale et al.[5]:

$$\dot{m}_p = \rho_w L_w A_m (\Delta P_m - \Delta \pi_m) \quad (14)$$

where the trans-membrane pressure ΔP_m is expressed as a function of the mass flow rate \dot{m}_f , the pressure P_f of the saline water, the pressure of the permeate that is supposed to be at atmospheric pressure, and the osmotic pressure $\Delta \pi_m$ that is function of the salt concentration and temperature of the feed water :

$$\Delta \pi_m = (C_f - C_p) RT_f \quad (15)$$

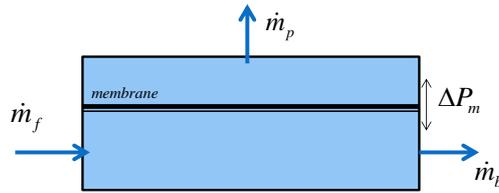


Fig. 3: schematic RO unit

3.4. Condenser

The modelling of the condenser, which is cooled by the pumped feed water, is quite similar to the one developed for the evaporator. However, it is assumed that the liquid level in the condenser is kept at a minimal value, at about 1% of the total volume of the condenser, in order to fulfil the thermodynamic equilibrium condition (both states are required).

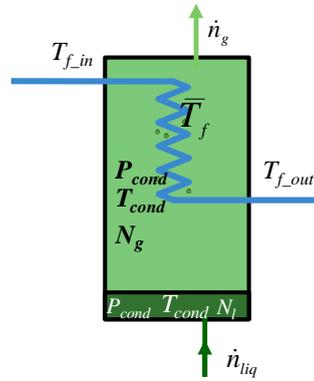


Fig. 4: Representation of the condenser

The excess liquid, which is produced by condensation of the vapour coming from the low pressure reservoirs, is transferred by gravity to a bottom receiver tank. The mass balance (15) is used to obtain the gas molar quantity present in the condenser.

$$\frac{dN_g}{dt} = \dot{n}_g - \dot{n}_{liq} \quad (15)$$

An enthalpy balance (16) is also applied to the condenser to determine its condensing temperature T_{cond} and pressure P_{cond} .

$$\frac{dU}{dt} = \dot{n}_g h_g - \dot{n}_{liq} h_{liq} - \phi_{cond} \quad (16)$$

As the feed water flows through the condenser at a temperature T_f close to the ambient one, in order to cool it, the condensation heat absorbed by the feed water can be expressed by considering the heat exchanger effectiveness ε_{cond} of the condenser :

$$\phi_{cond} = \dot{m}_f \cdot cp_f \cdot (T_{f_out} - T_{f_in}) = \dot{m}_f \cdot cp_f \cdot \varepsilon_{cond} (T_{cond} - \bar{T}_f) \quad (17)$$

The flow rate of pumped the feed water is given by the displacement speed and the volume chamber of the pumping hydraulic cylinder.

3.5. Hydraulic cylinders

In order to keep an identical operating during the two half cycles, that is to say the same involved saline volumes, the hydraulic cylinders are designed with three chambers in which each of them moves a piston (Fig 4).

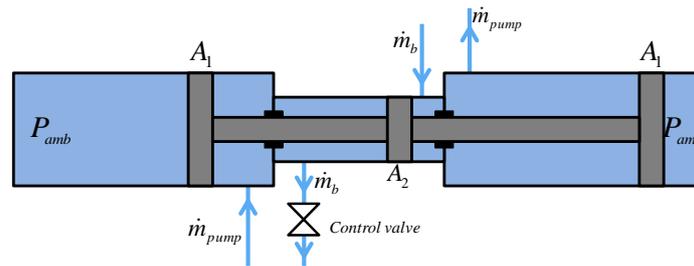


Fig. 5: Representation of the hydraulic cylinder

The central motive piston is set in motion thanks to the pressurized concentrated saline water flowing out the RO module. The movement of the piston rod enables in one hand to pump the feed water and store it in a first chamber of the hydraulic cylinder. Simultaneously, it enables also to transfer to the second reservoir the feed water that was previously stored in the third chamber of the hydraulic cylinder and pressurize it at the condenser pressure.

The displacement of the hydraulic cylinder is controlled by a control valve that keeps constant the mass flow rate of the exhaust water from the motive piston.

4. Results and discussions

This first modeling approach enables to simulate the process on a full day in order to analyze the dynamic behavior of this thermo-hydraulic solar driven desalination process. First simulations have been carried out with the physical parameters and simulation conditions summarized in table 1.

The thermodynamic properties of the working fluid (butane) and the saline water resulting from RefProp database (NIST database) have been considered [6].

A preliminary results permit to obtain a first design of the process, i.e. solar collector area of 2 m² and a 112 m² RO membrane, corresponding the entry parameters of Table 1.

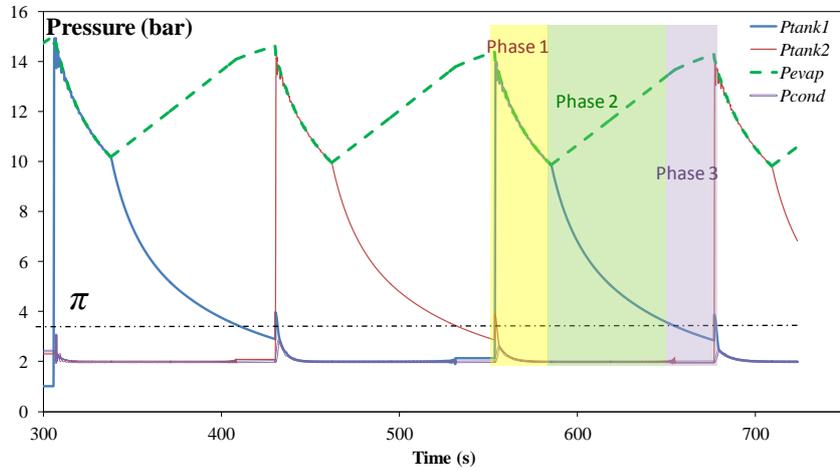
Table 1 : Simulation parameters

Description	Value
Working fluid	Butane
Feed water salinity	5 g.dm ⁻³
Feed water temperature	18°C
Feed tanks volume	25 liters
Membrane water permeability	2.7.10 ⁻¹² m ³ .s ⁻¹ .m ⁻² .Pa ⁻¹
Membrane salt rejection	99%
Water pumping pressure	0.9 bar

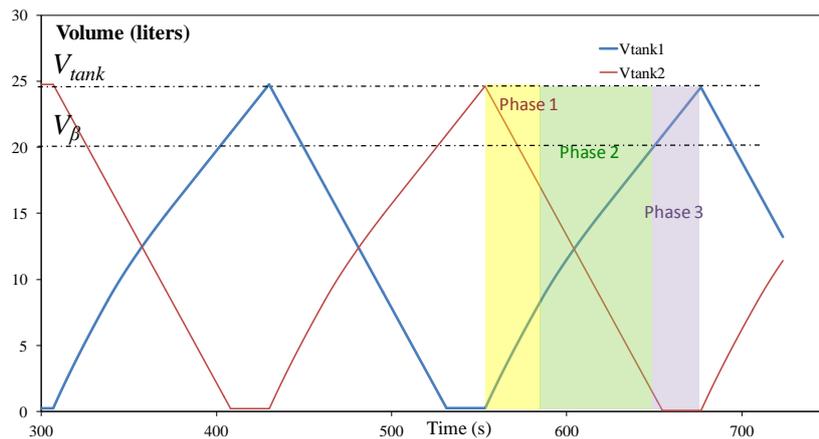
Fig. 6 shows the pressure and volumes evolutions in the main components of the process operating under a solar irradiation of 800 W/m². These results show a highly dynamic system with half-cycles of about 125s, corresponding to a first step of 33s, a second step of 40s and third step of 52s.

It appears in fig 6a that the evaporator enables efficiently the pressurization of the reservoir to nearly 15 bars, which is a sufficiently high pressure to ensure the desalination of the brackish water with a salt concentration of 5 g/l. It appears also that during the first step, which was previously considered to be taken place at a constant pressure, the pressure of the high pressure reservoir decreases showing thus that evaporator is not able to produce a sufficient amount of vapor to maintain the high pressure. The condenser pressure evolution shows that the mass flow rate of the pumped feed water is enough to cool it efficiently and maintain a stable condensing pressure.

Fig 6.b shows that at the end of phase 2, the discharge tank (tank 2) no longer contains gas, which means that it is full of feed water to be later desalinated. Phase 3 goes on until the feed tank (tank 1) is full of gas.



a)



b)

Fig. 6: Simulation results of the process operating under solar irradiation of 800 W.m^{-2} : a) pressure evolutions in the evaporator, the condenser and the reservoirs of the process, b) Gas volumes evolutions in the reservoirs, which volumes are 25 liters

Permeate production rate over time is also computed to estimate the daily clear water production represented Fig. 7. This intermittent production results in the variation of the pressurized reservoir. When the reservoir pressure becomes lower than the osmotic pressure, then no production of clean water is possible.

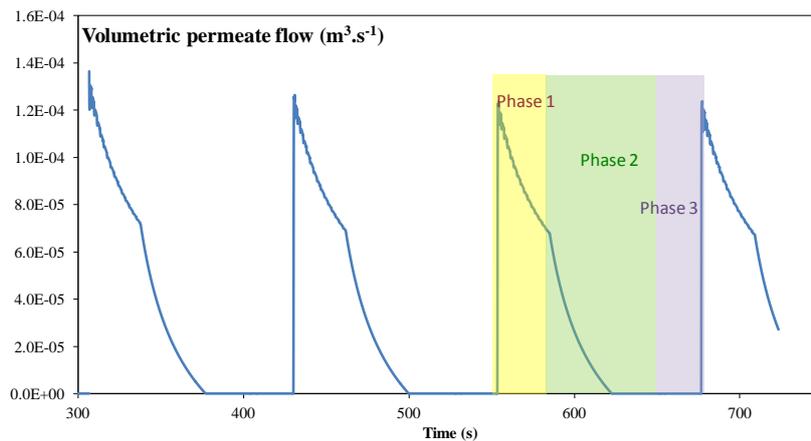


Fig. 7 : Evolution of the permeate production over time

A full day simulation allowed estimating the daily production to 743 liters of clear water for the process that operated during 136 cycles in the climatic conditions of Perpignan (France) with only 2 m² of solar collectors. The specific thermal energy consumption is evaluated to about 6.7 kWh per m⁻³ of produced clear water.

5. Conclusions and perspectives

Solar-driven standalone reverse osmosis (RO) desalination may be a promising and cost effective technology with a high potential for facing water scarcity and meet the water demand at small scale level (5-10m³/day) of population living in remote and isolated area. In this objective, there are more and more innovative desalination processes that are developed in the world, especially solar driven systems that are particularly relevant for areas that benefit of an important solar resource and where water is lacking. Moreover, autonomy and robustness are key parameters for developing such kind of solar desalination systems foreseen to be installed in totally off-grid areas.

Directly powering an RO device by low temperature heat, through an integrated thermodynamic engine cycle without energy storage can leads to drastic reduction of installation, maintenance and operating costs in comparison to current implemented PV/RO solution. The solar driven thermo-hydraulic process described in this study meets these objectives and can be a real alternative for a remote community by its autonomy coupled to low cost hydraulic components. Simple technology-based components have been chosen to ensure low investments and maintenance cost and avoid salt corrosion problems, the only parts that may suffer from corrosion are distributors and valves.

The first simulation results performances show that it is possible to produce approximately 750 liters per day from 5 g/l brackish water by such kind installation implementing only 2 m² of solar collectors. These results demonstrate that this innovation may be competitive in comparison to other renewable driven desalination systems. These numerical results correspond to a brackish water application. Deepest simulations have to be led and crossed with experimental results in order to confirm these promising results. A dynamic model of the RO membrane is currently developed and under experimental validation. Next simulations will use a more precise dynamic model and will be extended to seawater desalination.

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Nomenclature

A	area, m ²
C	concentration, kg/kg
C_p	mass specific heat, J/(kg K)
h	molar enthalpy, J/mol
I	solar irradiance, W/m ²
L_w	water membrane permeability, m ³ /(m ² s Pa)
L_s	salt membrane permeability, m ³ /(m ² s)
M	mass, kg
\dot{m}	mass flow rate, kg/s
N	molar quantity, mol
\dot{n}	molar flux, mol/s
P	pressure, Pa
R	ideal gas constant, J/(mol K)
R_s	membrane salt rejection
T	temperature, °C
\bar{T}	solar collector mean temperature, °C
U	internal energy, J
V	volume, m ³

Greek symbols

α	phase 1
β	phase 2
ε	heat exchanger effectiveness
η	solar collector efficiency
ϕ	incident heat flux, W
π	osmotic pressure, Pa

Subscripts and superscripts

amb	ambient conditions
b	brine
c	solar collector
cond	condenser
ev	evaporator
f	feed water
g	gas
h	high
in	input
l	low
liq	liquid
m	membrane
out	output
p	permeate
pump	pumped
s	salt
tank	tank
v	vapour or control valve

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