Dynamic Numerical Simulation of a Mechanical Vapour Compression (MVC) Desalination System That Use Renewable Source Energy

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Abstract

This paper presents a numerical model to analyse the thermal and fluid dynamic behaviour of a mechanical vapour compression MVC desalination system, which uses renewable energy to supply the electricity required by the whole system. The reason to use renewable energy is that the MVC desalination system has been though to work in remote places, where an electric grid is not available. The transient and steady-state of the desalination system are evaluated taking into account the variability of the renewable energy sources (solar energy). A scalability study has been carried out to find the relation between the variability of the renewable energy sources and the capacity of the desalination system (distilled water production). Different components which making up the desalination system are considered in the numerical simulation, all of them are solved in a coupled way by mean of an object-oriented tool called NEST. The influence of the feed seawater conditions is also analysed on the system performance.

Key-words: MVC desalination unit; Numerical modelling; Dynamic performance; Renewable source energy.

1. Introduction

The MVC desalination method is an evaporation and condensation process that occurs at low pressure, which requires a compression work to increase the saturation temperature of the vapour. The trend is to use low evaporation temperatures (between 50 to 70^{o}C) to reduce the risk of corrosion and scale deposition (El-Khatib 2004). The compressed vapour is condensed and its latent heat is transferred to the feed seawater. The applicability of MVC desalination systems in remote places where there is not possible a connection to an electric grid depend on the use of renewable energy sources. However, the renewable energy means variability in the power given. This variability should be well defined to avoid damage and establish secure partial working operation of the desalination system. The MVC desalination is used at low and medium scale in comparison with other techniques such as: multistage flash desalination (MSF) or reverse osmosis (RO) (Ettouney, 2006).

The numerical modelling presented in this paper is applied to analyse the thermal and fluid dynamic behaviour of a MVC desalination system, which uses renewable energy source (solar energy) to supply the electric requirements of the system. The electrical energy is used to feed the mechanical compressor, a heater, a group of pumps and the control panel of the system. The well-known variability of renewable sources of energy is considered in the performance system study. Also, the influence of the boundary conditions on the execution of the unit along the time is analysed.

2. Dynamic modelling

The desalination system has been divided in four different subsystems, following the strategy proposed by Bodalal (2010) and Mazini (2014). The first subsystem is the evaporator and condenser, in which the evaporation and distillation processes are performed. The second is the vacuum and deareation subsystem, where the low pressure is achieved and non-condensed gas (Oxygen) is stripped. The third subsystem is the mechanical compressor, which is modelled to know its energetic requirement in function of the desalination performance and the climatic conditions. The last subsystem is the heat exchangers, which preconditioning the feed seawater flow temperature, taking advantage of the heat contained in the distilled water and brine flows at the outlet of the evaporator/condenser.

The evaporator and condenser subsystem is modelled describing it as a brine block, vapour space block, and a tube bundle. A schematic representation of these blocks is depicted in Figure 1, together with the others

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subsystems. The vacuum and deareation subsystem is modelled assuming that there are a liquid block, a vapour space block and a package zone, which are depicted in Figure 2. The compressor has been modelled following the mechanical model of a rotatory lobe compressor (blower), which uses the geometric configuration and the relation between velocity (rpm) and the displacement by revolution (cfr) of the compressor.

3. Mathematical formulation

The mathematical formulation of the evaporator/condenser subsystem is based on mass, and energy balance conservation equations.

$$\frac{dm_V}{dt} + \frac{dm_B}{dt} + \dot{m}_B + \dot{m}_{Do} - \dot{m}_{Fi} = 0 \qquad \text{(eq. 1)}$$

$$\frac{dm_V h_v}{dt} + \frac{dm_B\, h_B}{dt} + \frac{dm_{VT}\, h_T}{dt} + \dot{m}_B h_B + \dot{m}_{Do} h_{Do} - \dot{m}_{Fi}\, h_{Fi} = 0 \qquad \text{(eq. 2)}$$

Mass and energy conservation equations of vapour space

$$\frac{dm_V}{dt} + \dot{m}_D + \dot{m}_{v2} + \dot{m}_{nc} - \dot{m}_V - \dot{m}_{nc} = 0 \qquad \text{(eq. 3)}$$

$$\frac{dm_v\, h_V}{dt} + \dot{m}_D\, h_V + \dot{m}_{v2}\, h_V + \dot{m}_{nc} h_V - \dot{m}_V\, h_V - \dot{m}_{nc} h_V = 0 \qquad \text{(eq. 4)}$$

Mass, energy and salt conservation equation of the brine lump

$$\frac{dm_B}{dt} + \dot{m}_B + \dot{m}_{Fr} - \dot{m}_{Fo} - \dot{m}_C = 0 \qquad \text{(eq. 5)}$$

$$\frac{dm_B\, h_B}{dt} + \dot{m}_B h_B + \dot{m}_{Fr} h_B - \dot{m} h_{Fo} - \dot{m}_C h_B = 0 \qquad \text{(eq. 6)}$$

$$\frac{dm_B\, X_B}{dt} + \dot{m}_B X_B + \dot{m}_{Fr} X_B - \dot{m}_{Fo} X_{Fo} - \dot{m}_C X_C = 0 \qquad \text{(eq. 7)}$$

Mass of the bundle tubes and energy conservation equation of the vapour condensed inside tubes, assuming that there is not heat accumulation in solid walls.

$$\frac{dm_T}{dt} = 0 \qquad \text{(eq. 8)}$$

$$\frac{dm_{VT} h_T}{dt} + \dot{m}_{Do} h_{Di} - \dot{m}_{Do} h_{Do} = -\dot{Q}_e \text{ evaluating } \dot{Q}_e = U_T A_T (T_D - T_B) \qquad \text{(eq. 9)}$$

The heat transferred between the vapour condensed inside of the bundle tubes and the fluid outside of tubes is defined in function of the global heat transfer coefficient, transfer area and the difference temperatures. Assuming that the tubes cannot accumulate salt on the external surface, then

$$\dot{m}_C X_C - \dot{m}_{Fr} X_B = 0 \qquad \text{(eq. 10)}$$

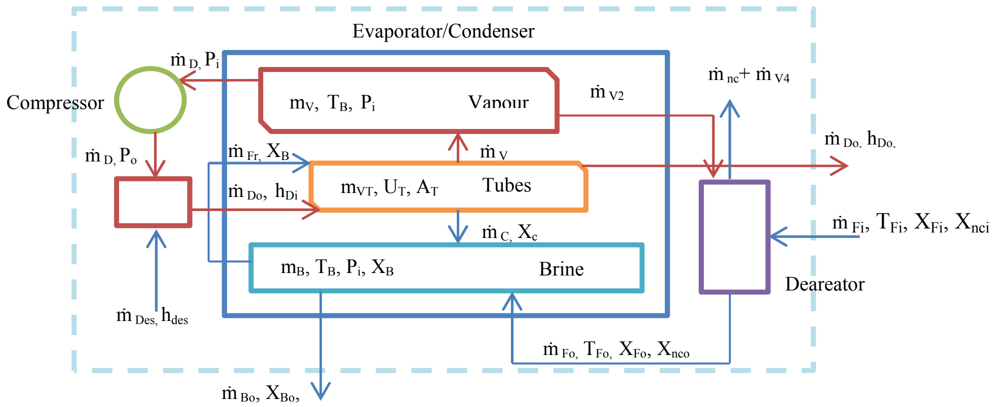


Fig. 1: Schematic representation of the MVC desalination system and evaporator/condenser subsystems

The mathematical formulation of the vacuum and deareation subsystem is based on the same mass, energy and salt balance conservation equations applied on the vapour, liquid and packed zone. The conservation equations are applied on the package zone assuming that there is not accumulation of mass, energy or salt on it. Some extra relations are used to define the value of the non-condensable gas stripped, the flash evaporation, the mass flow condensed into the package and the mass flow at the outlet of the deareator (Suryanarayana, 2011).

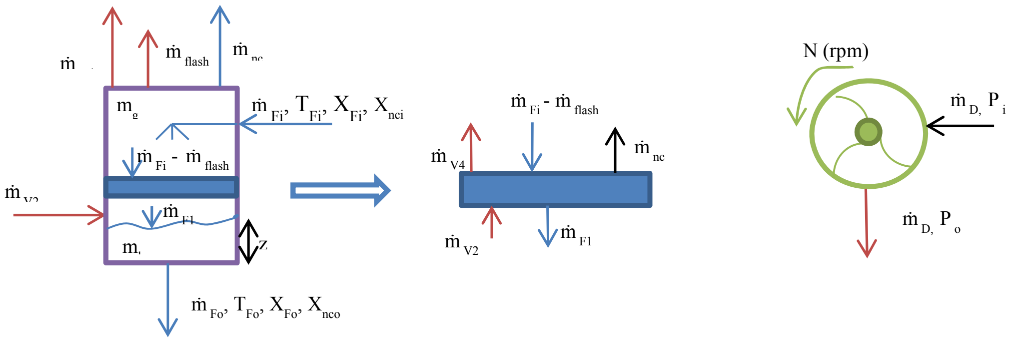


Fig. 2: Schematic representation of the deareator subsystem (including a detail of the package zone) and the compressor

$$\frac{\partial m_g}{\partial t} + \dot{m}_{v4} + \dot{m}_{v3} - \dot{m}_{flash} - \dot{m}_{v2} = 0 \qquad \text{(eq. 11)}$$

$$\frac{\partial m_l}{\partial t} + \dot{m}_{Fo} - \dot{m}_{F1} = 0 \qquad \text{(eq. 12)}$$

$$X_{nco}\frac{\partial m_l}{\partial t} + m_l\frac{\partial X_{nco}}{\partial t} + \dot{m}_{Fo}X_{nco} - \dot{m}_{F1}X_{nc1} = 0 \qquad \text{(eq. 13)}$$

$$\frac{\partial m_g h_g}{\partial t} + \dot{m}_{v4}h_g + \dot{m}_{v3}h_f - \dot{m}_{flash}h_g - \dot{m}_{v2}h_g = 0 \qquad \text{(eq. 14)}$$

$$\frac{\partial m_l h_{fo}}{\partial t} + \dot{m}_{Fo}h_{fo} - (\dot{m}_{Fi} - \dot{m}_{flash})h_{fi} - \dot{m}_{v3}h_f = 0 \qquad \text{(eq. 15)}$$

Assuming that there is not accumulation on package zone:

$$\dot{m}_{F1} - (\dot{m}_{Fi} - \dot{m}_{flash}) - \dot{m}_{v3} = 0 \qquad \text{(eq. 16)}$$

$$\dot{m}_{v4} + \dot{m}_{v3} - \dot{m}_{v2} = 0 \qquad \text{(eq. 17)}$$

$$\dot{m}_{F1}X_{nc1} + \dot{m}_{nc} - (\dot{m}_{Fi} - \dot{m}_{flash})X_{nci} = 0 \qquad \text{(eq. 18)}$$

$$\dot{m}_{F1}h_{f1} - \dot{m}_{v3}h_f - (\dot{m}_{Fi} - \dot{m}_{flash})h_{fi} = 0 \qquad \text{(eq. 19)}$$

$$\dot{m}_{v4}h_g + \dot{m}_{v3}h_f - \dot{m}_{v2}h_g = 0 \qquad \text{(eq. 20)}$$

Where:

$$\dot{m}_{v3}h_{fg} = \dot{Q}_{cond} = \alpha_i A_i (T_{sat} - T_{fi}) \qquad \text{(eq. 21)}$$

$$\dot{m}_{flash} = \frac{C_p\,(T_{sat} - T_{fi})}{h_{fg}}\,\dot{m}_{Fi} \qquad \text{(eq. 22)}$$

$$\dot{m}_{nc} = K_l A_c \Delta X_{Ln} \qquad \text{(eq. 23)}$$

Evaluating: $\Delta X_{Ln} = \frac{[(X_{nci} - X^*_{nci}) - (X_{nco} - X^*_{nco})]}{ln[(X_{nci} - X^*_{nci})/(X_{nco} - X^*_{nco})]}$

$$\dot{m}_{Fo} = f(valve) = \sqrt{2gz}\,A_{valv}\,\rho \qquad \text{(eq. 24)}$$

The compressor (blower) model is based on the root blower laws, in which the volumetric flow, velocity, power and the displacement by revolution values are related:

$$\dot{V} = cfr * (rpm - Slip_{corrected}) \qquad \text{(eq. 25)}$$

$$Power = [0.00436 * cfr * rpm * (P_o - P_i)] + Friccional\ loss \qquad \text{(eq. 26)}$$

The ideal gas law is used to evaluate the inlet pressure at the compressor as function of the vapour mass contained into the evaporator, the temperature of the vapour and the volume occupied.

$$P_i = \frac{1}{V_v}\frac{m_v}{M}RT \qquad \text{(eq. 27)}$$

The heat exchangers are evaluated in function of heat flux transferred between flows (distilled water, brine and feed seawater) to obtain the temperatures of each one, using the overall heat transfer coefficient (U), the logarithm mean temperature difference (LMTD) and the transfer area (A_{Hex}). Assuming the hypothesis that there is not heat losses in the heat exchangers, the heat transferred should be equal to the heat flux obtained or delivered for the flow.

$$Q_{exchanged} = U\, A_{HEX}\, LMTD = \dot{m}\, C_p (T_{in} - T_{out}) \qquad \text{(eq. 28)}$$

4. Numerical resolution

The group of equations is solved by means of the in-house object-oriented tool called NEST, which is capable to link and solve different elements that making up a system (Damle, et. al., 2011; Farnós, et. al., 2014). The MVC desalination system that is presented in this paper has different components: an evaporator/condenser, a compressor, a deareator, two heat exchangers and a group of pumps. Although in this numerical platform each component is an object, the whole system resolution is carried out iteratively by solving all its components and transferring the appropriated information between them (see Figure 3).

A dynamic model based on mass, energy and salt balances and applied to internal components of the MVC desalination system has been implemented to analyse the transient behaviour of the MVC desalination system, which uses renewable source energy.

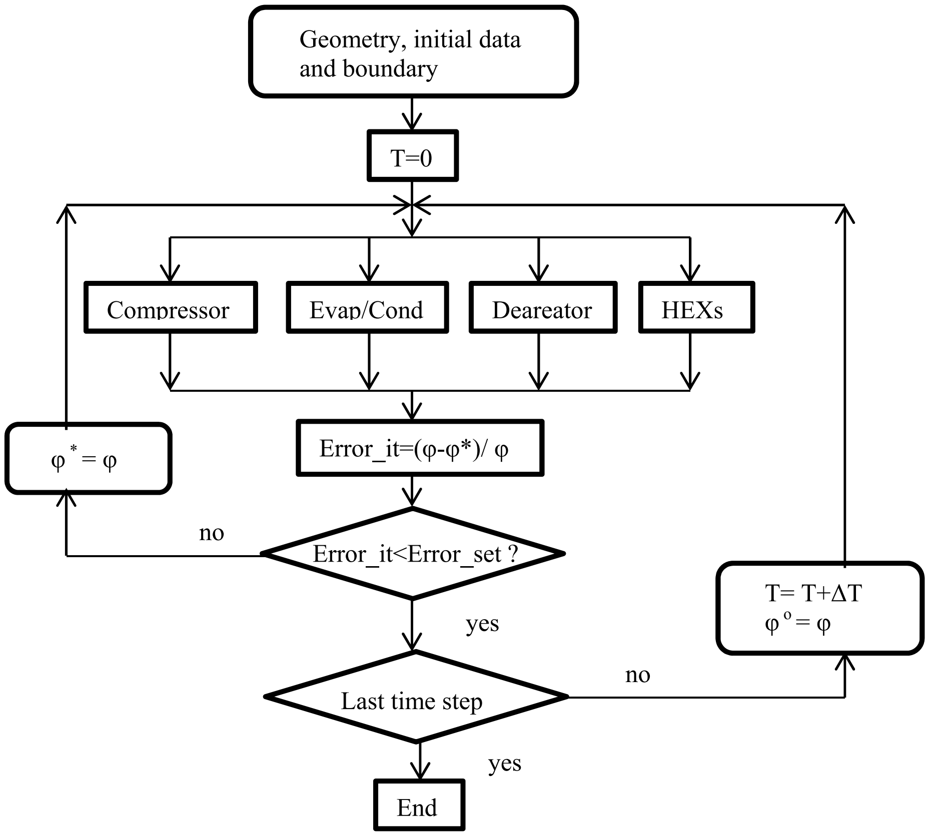


Fig. 3: Global algorithm to solve the MVC desalination unit

5. Results

A numerical analysis has been carried out to define the specific average consumption of the MVC desalination systems analysed. A value of 15.08 kW/m^3 has been defined including the power required by the compressor, pumps and heater of the whole system. A scalability study using three different units, each one with a production capacity of 100, 200 and 400 m^3/day of distilled water, has given 14.98, 15.07 and 15.19 kW/m^3, respectively. All these values are in agreement with technical literature data (Plantikow, 1999). The numerical results expressed in a percentage relation between the energy used and the distilled water production is depicted in Figure 4. This graphic shows the capacity of supplying distilled water in function of the energy source variability; as an example a reduction of 70% in the energy source represents a decreasing of 58% in the production capacity of distilled water. This value is in agreement with data proposed by Plantikow (1999) for a specific case in which evaporation occurs at 60°C.

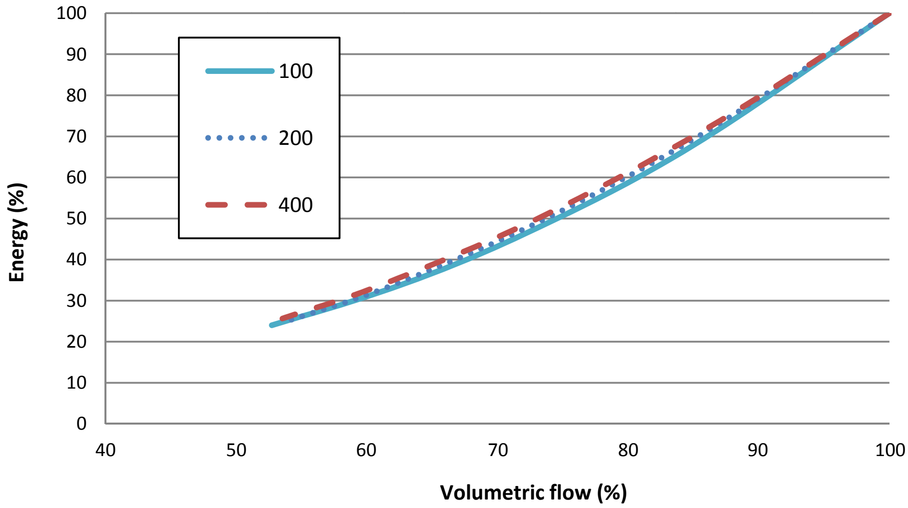


Fig. 4: Percentage relation between energy requirement and volumetric flow demand of the MVC desalination system

A virtual prototype desalination unit capable to produce 1m^3/day of distilled water has been used to evaluate the preliminary results under dynamic conditions. Three different cases have been used to evaluate the thermal behaviour of the MVC desalination unit, in which an evaporation temperature about 60°C has been used.

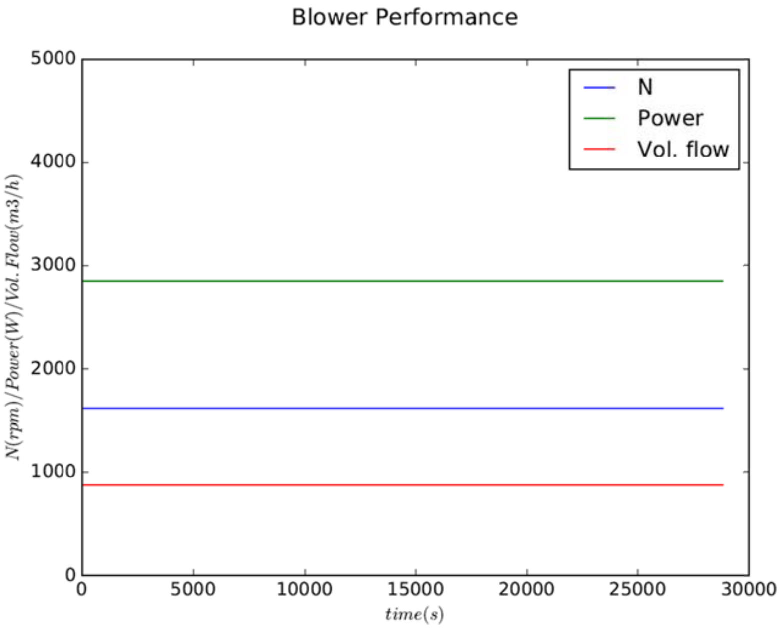


Fig. 5: Compressor (blower) performance: Velocity (N), Power availability (Power) and Volumetric Flow (Vol. Flow)

The first case consist of evaluating the energy required to produce 1m^3/day of distilled water, assuming a complete availability of the energy and constant power (a hypothetical condition: how if the unit will be connected with an electrical grid). The power, the velocity and the volumetric flow of the compressor are shown in Figure 5. A constant power produces not variations in the velocity and the volumetric flow, which produce that the MVC desalination unit works in stable conditions using a constant mass flow of feed seawater during the working time. The total mass of the seawater required to produce 1m^3 of distilled water is depicted in Figure 6, together with the mass of brine and distilled water produced in the process.

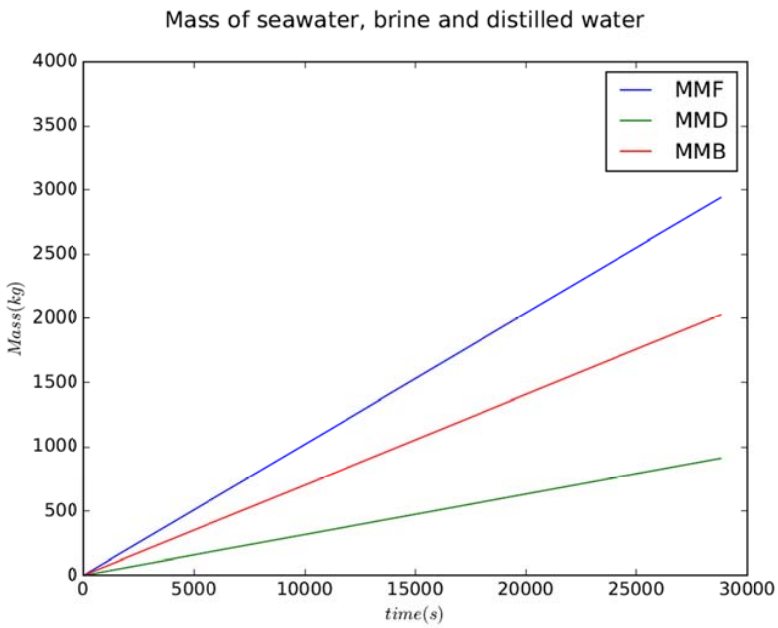


Fig. 6: Masses used by the MVC desalination unit along 8 hours: distilled water (MMD), brine (MMB) and seawater (MMF)

The pressures and the temperatures in the evaporator and condenser of the MVC desalination unit keep their values along the process, achieving a steady state conditions until produce the quantity of distilled product defined. In this case a power of 2850W is required to produce around 1m^3 of distilled water in 8 working hours.

The second case consists of analysing the influence of the energy availability and variability on the compressor performance and their effect on the thermal behaviour of the MVC desalination system. The solar energy is used as source energy of the MVC desalination system in which the energy availability is obtained from meteorological data, assuming that the desalination plant works in Barcelona-Spain (See Table 1).

Tab. 1: Meteorological data for Barcelona on June

Hour	Radiation (W/m^2)	Ambient Temperature (°C)
9:00	515	17.2
10:00	684	18.1
11:00	771	19.8
12:00	860	20.6
13:00	811	21.1
14:00	801	21.9
15:00	734	22.0
16:00	722	20.9

A group of photovoltaic devices should be used to transform the solar radiation in electrical energy, which will be used to feed the compressor and pumps. The radiation data is a parameter needed to evaluate the energy source, together with the photovoltaic panel efficiency and the effective area used. The electric power evaluated is used to calculate the compressor velocity and the volumetric flow displaced. A sunny day of June has been chosen to evaluate the energy availability and variability along the day. Eight hours have been simulated with the aim of obtaining 1.0m^3/day of distilled product.

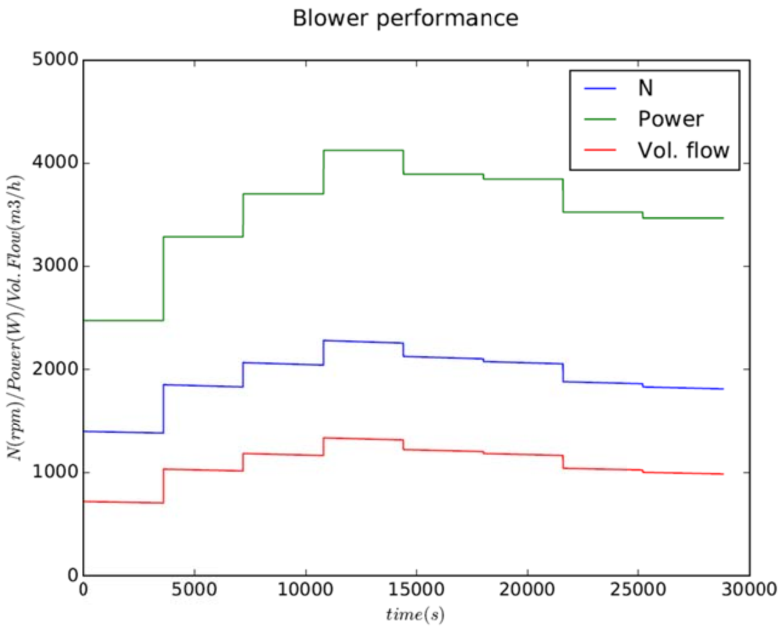


Fig. 7: Compressor (blower) performance: Velocity (N), Power availability (Power) and Volumetric Flow (Vol. Flow)

The compressor performance and the thermal behaviours of the MVC desalination unit are described in next figures. The velocity of the compressor and the volumetric flow are function of the solar energy available, which is defined by a power profile that manages the compressor performance along the 8 working hours.

The volumetric flow moved from the compressor to the evaporator/condenser defines the thermal behaviour of the MVC desalination unit, which requires a specific quantity of the seawater to feed the unit and to produce the distilled water. The mass flows used by the MVC desalination unit are depicted in Figure 8.

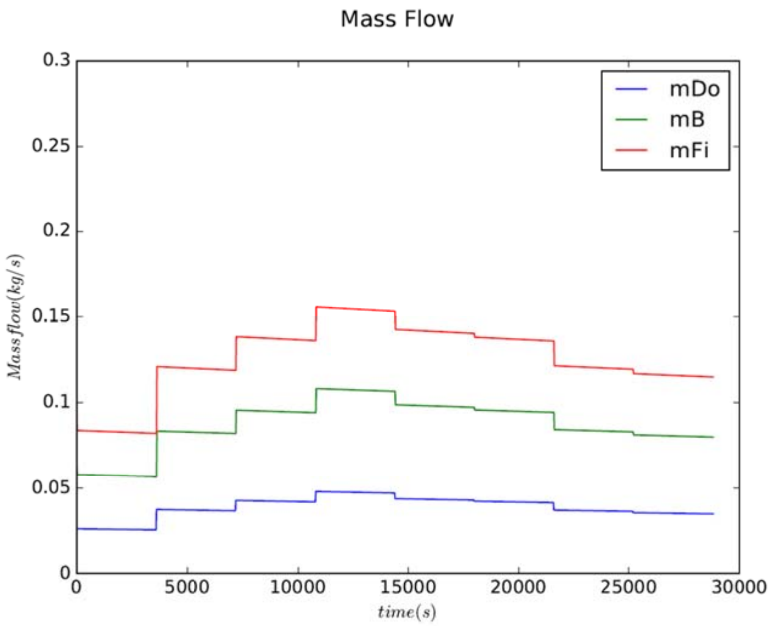


Fig. 8: Mass flows used by the MVC desalination unit: distilled water (mDo), brine (mB) and feed seawater (mFi)

The total mass of seawater needed to produce 1.0 m3 of distilled water (final product) together with the quantity of brine produced in the desalination process can be obtained after integrating the mass flows along the time. The masses of seawater, brine and distilled water are shown in Figure 9, a slight change can be observed if the results are compared with the results of the case with constant power (see Figure 6).

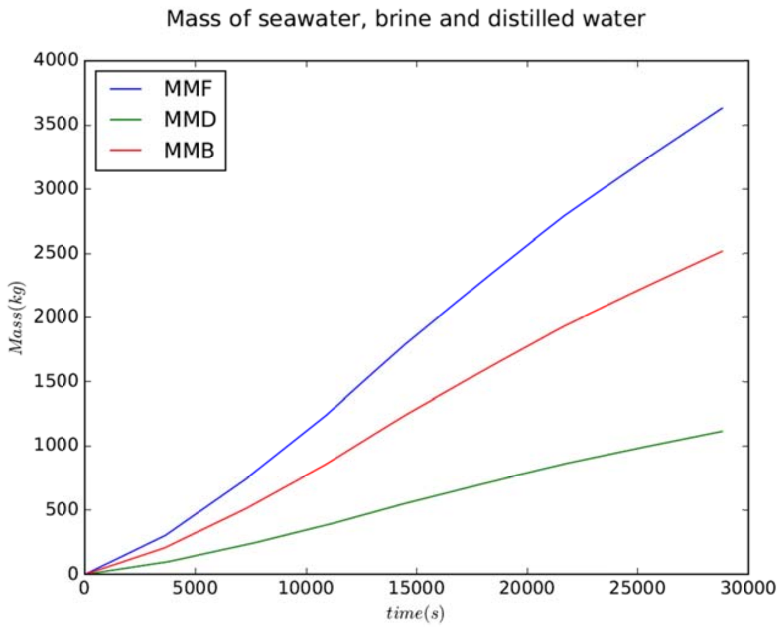


Fig. 9: Masses used by the MVC desalination unit along 8 hours: distilled water (MMD), brine (MMB) and seawater (MMF)

The salt concentration of the recirculation, brine and feed seawater flows are shown in Figure 10. A constant salt concentration value of the feed seawater at the inlet is used, whilst the salt concentration values of recirculation and brine flows present a slight decrease following the same tendency of the pressure in the evaporator.

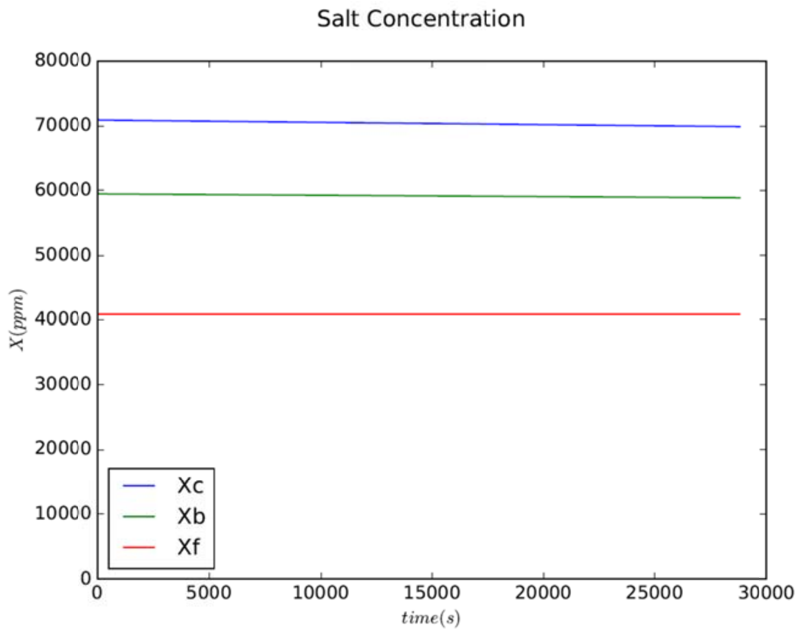
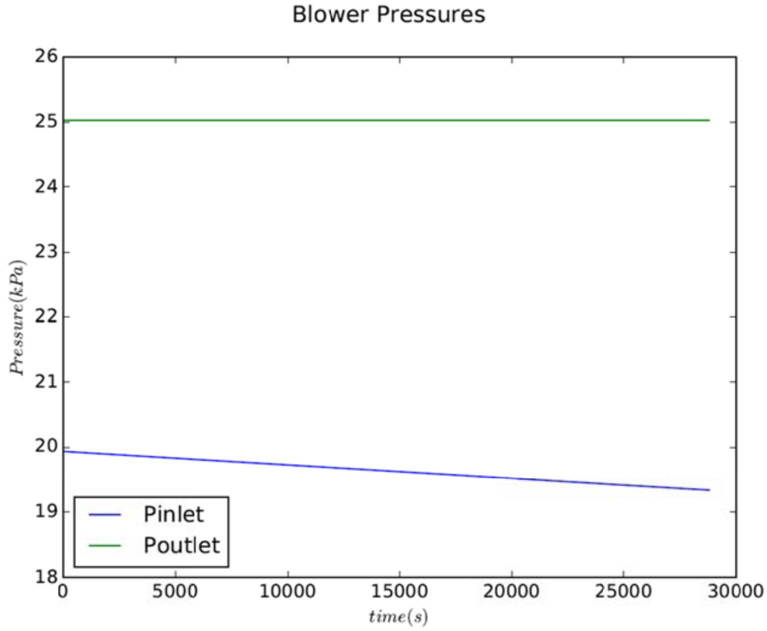


Fig. 10: Salt concentration in the evaporator/condenser: recirculation flow (Xc), brine flow at the outlet (Xb) and feed seawater flow at the inlet (Xb)

The temperatures and pressures into the evaporator/condenser are shown in Figure 11. The vapour, brine and feed seawater temperatures present a stable behaviour as consequence of the evaporation pressure (Pinlet) and condensation pressure (Poutlet) used in the process. A small decrease in the evaporation pressure and temperature are detected, which produces that the differential pressure increase its value, reducing the volumetric flow in the compressor and the mass flows in the MVC desalination unit (see Figures 7 and 8).



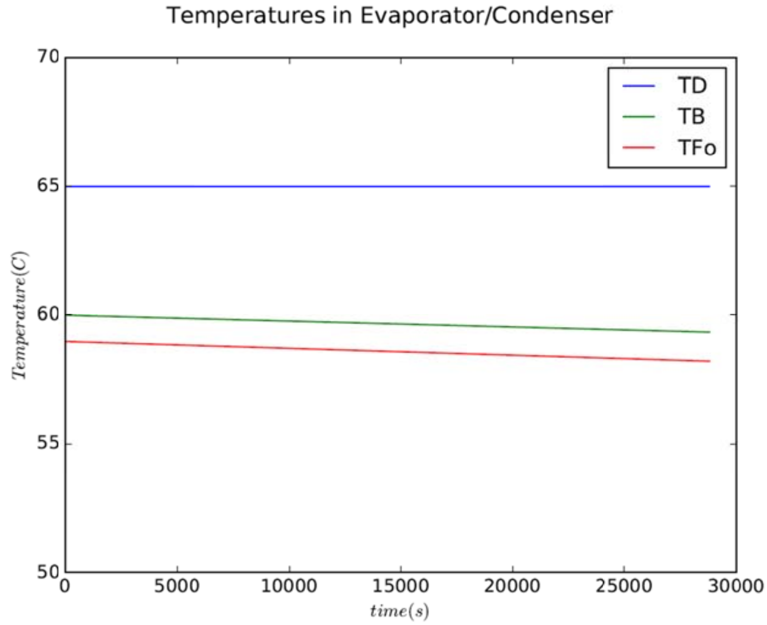


Fig. 11: Temperatures in the evaporator/condenser: vapour (TD), brine (TB) and feed seawater (TFo) and pressures in the blower

The energy transferred between the feed seawater, the distilled water and brine flows in the heat exchangers produce that the seawater increases its temperature from T_{CW} to T_{FI}, whilst the distilled water and brine flows decrease their temperatures from T_D and T_B to T_{DO} and T_{BO}, respectively. The temperature profiles are function of the different mass flows used by the MVC desalination unit, as consequence of the power variability along the working time. These temperatures are shown in Figure 12.

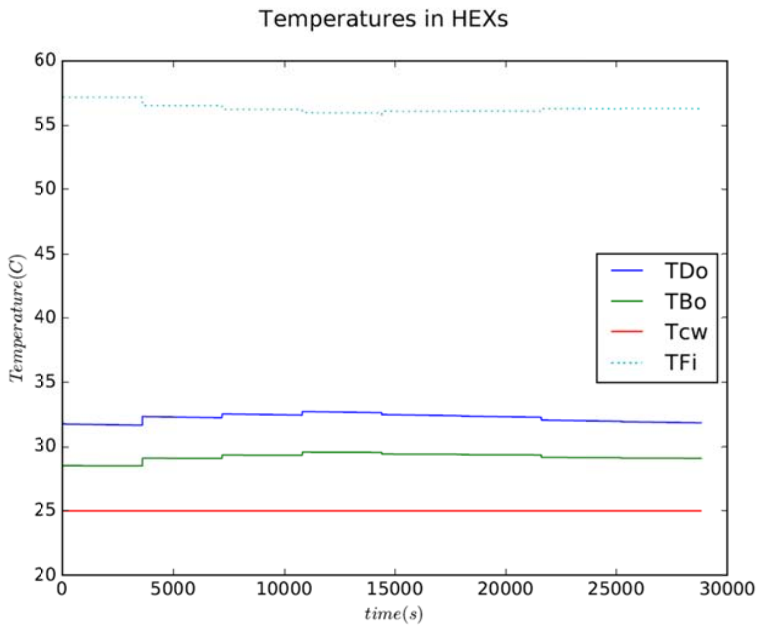


Fig. 12: Temperatures in the heat exchangers of the flows along 8 hours: distilled water at the outlet (TDo), brine at the outlet (TBo), preheating seawater at the outlet (TFi) and feed seawater at the inlet (Tcw)

The third case consists of analysing the influence of the boundary conditions, the feed seawater temperature (T_{CW}) and its salt concentration (X_f) at the inlet of the system, on the distilled water and brine flows at the outlet of the system. Regularly a change in the boundary conditions is applied, details in Table 2.

Tab. 2: Boundary conditions applied in function of time

Hour	Seawater Temperature T_{cw} (°C)	Salt Concentration X_f (ppm)
1	25.0	41000
2	25.5	42000
3	26.0	42500
4	27.0	43000
5	27.0	43000
6	26.5	42500
7	26.0	42000
8	25.0	41500

The numerical results of the third case are depicted in Figures 13 and 14. The salt concentration of the brine flow (Xb) at the outlet of the unit and the salt concentration of the recirculation flow (Xc) are shown. The salt concentration values tend look for a new steady-state condition along the time, keeping the difference regarding to the salt concentration of the feed seawater at the inlet.

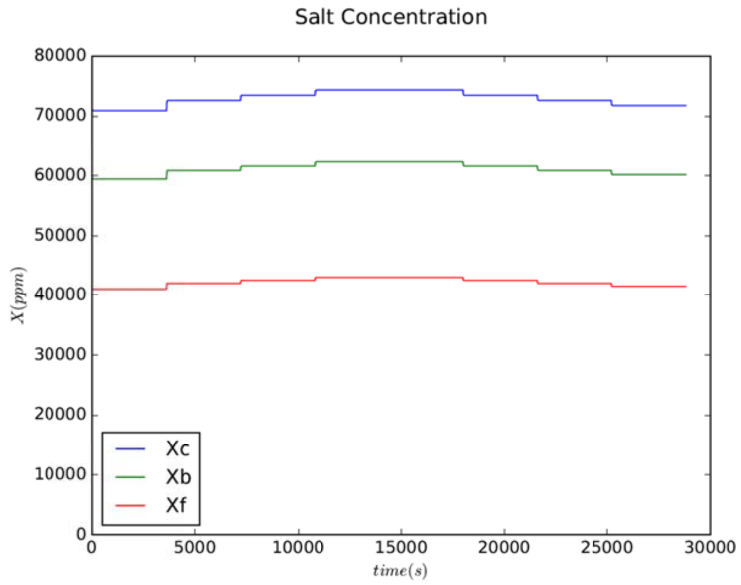


Fig. 13: Dynamic behaviour of the salt concentration in the MVC desalination system

The temperatures of the distilled water, brine and feed seawater flows after pass through the preconditioning heat exchangers are shown in Figure 14. The temperature profiles of the flows depend on the feed seawater conditions (T_{CW}) at the inlet of the MVC desalination unit.

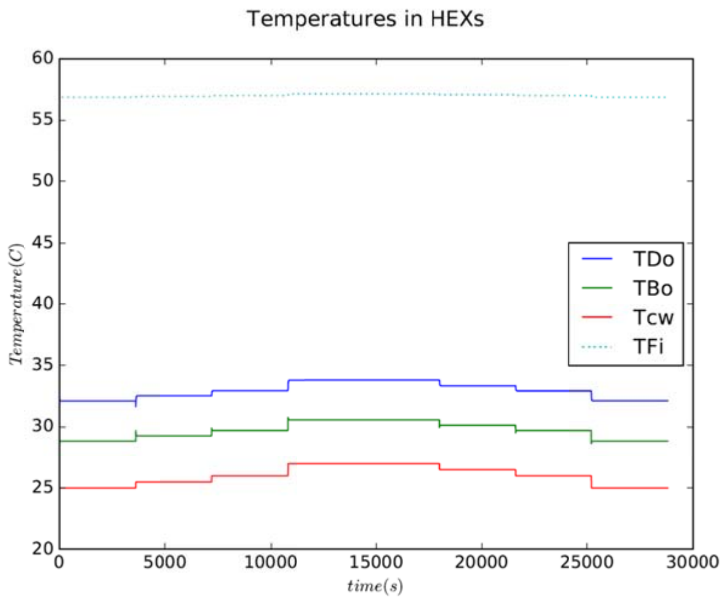


Fig. 14: Dynamic behaviour of the temperatures in the heat exchangers of the MVC desalination system

6. Conclusions

A model to simulate the dynamical behaviour of a MVC desalination unit has been implemented and the numerical results have been presented in this paper. The numerical model proposed is a powerful tool to evaluate the thermal and dynamical performance of the MVC desalination unit working under variable conditions. Three different cases have been simulated with the aim of describing the compressor and MVC desalination unit performance under different conditions of power or boundary conditions.

The mass flows used by the MVC desalination unit depend on the energy used by the compressor during the working period, whilst the temperatures, pressure and salt concentrations into the evaporator/condenser are independent of this value.

The salt concentrations of the flows into the evaporator/condenser depend on the boundary conditions applied at the inlet of the MVC desalination system. The third case shows the variation of the salt concentration of the brine in function of the salt concentration of the feed seawater (X_f).

The temperatures of the distilled water and brine flows at the outlet of the system and the preheated seawater temperature at the inlet of the evaporator/condenser are function of the mass flows used by the MVC desalination unit and depend on the feed seawater temperature (T_{CW}) at the inlet of the precondition heat exchangers.

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